The development of modern management tools and their specific requirements for the assessment of recyclability of products

Recycling-Oriented Assessment Tool
ReOAT V.0.9

Von der Fakultät für Umweltwissenschaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus zur Erlangung des akademischen Grades eines PhD-Degree genehmigte Dissertation

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Tag der mündlichen Prüfung: 7 April 2006

DECLARATION

I hereby declare that this dissertation is solely the result of my own effort and all other sources/works used have been adequately referenced. This research leading to this dissertation was carried out under the supervision of Prof. Dr. rer. nat. Jürgen Ertel and Prof. Dr. rer. nat. Gerhard Wiegleb.

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DEDICATION

I dedicate this work to my parents.

DISCLAIMER

ABSTRACT

Environmental consciousness of the modern society has projected recycling into the limelight as it has considerable potential for saving the earth's limited resources, and potential offers opportunities for reducing environmental pollution. This dissertation presents a methodology developed for assessing the recycling-orientation of products in product design and a tool for carrying out the assessment. The design criteria for the recycling-orientation of products are formulated by investigating and analysing relevant product design constraints, including standards and regulations that facilitate and ease recycling. Essentially, this final dissertation comprises two parts: (1) the dissertation manuscript, (2) the assessment tool, "software." The dissertation expatiates on the methodology employed and its implementation details for assessing the recycling-orientation of products both qualitatively and quantitatively at the design stage. Several recycling related product design standards were taken into account, including WEEE, RoHS, Eco-design, and DFR. The software comprises a series of decision stages; each stage controls different active facets of its functionalities. The assessment of the recycling-orientation of product design is achieved by virtually modeling a product from the product profile. The detail of how this works is demonstrated with a case problem. The opportunity for future development and software upgrading are discussed at the end.

ABSTRAKT

Das Umweltbewusstsein der heutigen Gesellschaft führte dazu, die Wiederverwendung (Recycling) von Abfall ins öffentliche Interesse zu stellen, die ein beträchtliches Potential für die Schonung von begrenzten natürlichen Ressourcen und Verminderung der Umweltbelastungen birgt. Diese Dissertation zeigt eine Methodik auf, um die Recyclingeignung von Produkten schon während der Produktentwicklung zu beurteilen. Hierfür wurde insbesondere ein Tool zum Durchführen der Einschätzung entwickelt. Die Designkriterien für recyclingorientierte Produkte wurden durch die Analyse der vorhandenen Bedingungen für die Produktentwicklung aufgestellt. Diese Bedingungen sind u.a. in Standards, Normen oder der Gesetzgebung verankert. Im Wesentlichen besteht die Dissertation aus zwei Teilen: [1] das Dissertationsmanuskript, [2] das Bewertungstool „Software“. Diese Dissertation beschreibt die Anwendungsbedingungen der Methodik und Software. Weiterhin werden Details zu ihrer Implementierung bei der Bewertung der Recyclingeignung von Produkten während der Entwicklung [sowohl quantitativ als auch qualitativ] beschrieben. Verschiedene Vorgaben zum recycling-orientierten Produktdesign einschließlich WEEE, RoHS und DFR wurden berücksichtigt. Die Software enthält eine Serie von Entscheidungsstadien, in der jede Entscheidung die Aktivierung von unterschiedlichen Funktionen bestimmt. Die Beurteilung der Recyclingorientierung eines Produkts wird erzielt, indem praktisch ein Produkt vom Produktprofil an modelliert wird. Die Funktionsweise des Programms wird mit Hilfe eines Problemfalls demonstriert. Die Möglichkeiten für zukünftige Entwicklungen und Software-Upgrades werden am Ende besprochen.

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I want to acknowledge my colleagues who were always available to discuss academic, research and other pertinent issues; I could not have acclimatized and enjoyed life at BTU Cottbus if it was not for the wonderful support I had from the Department of Industrial Sustainability staff. In particular for the support I had from the university I would like to thank the ERM administrator and PhD coordinator who had been very helpful and available for discussion on educational aspects. I also would like to thank ERM PhD Programme, and the Department of Industrial Sustainability once again for their partial and full financial support on several activities during my PhD study such as: international conferences (Electronics Goes Green, EGG2004+, Germany; 11th Annual International Sustainable Development Research Conference, SDRC-2005, Finland; and Industrial Symbiosis Research Symposium, ISRS-2005, Sweden); PhD workshops (St. Marienthal's Convent, Germany; and Birmingham University, the United Kingdom); and research studies abroad (data collection and discussion with related industrial and recycling business, Thailand).

I am thankful for my friends, teachers, students, and academic collaborators from Germany, Thailand, and other countries. Their support and company kept me grounded and helped me to be appreciative of life. Thank you to Mr. Raymond Babanawo for his proof reading and comments to this work.

I am indebted to my family for the love and support during my six years at BTU Cottbus. I am forever grateful for the phone calls, visits and gentle handling from them all. The firm support, love and faith from Mom, Dad and Sister, Brother in law both motivated and anchored me. I could not have accomplished this dissertation without having them in my corner.

Lastly, to all of those acknowledged here and others, thank you for being you and letting me be a part of your lives.

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ACRONYMS/ABBREVIATIONS

ActiveX Component	encompassing ActiveX EXE, ActiveX DLL, ActiveX Control
ActiveX Control	means active events when react by mouse, keyboard
ADO	ActiveX Data Objects
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CP	Cleaner Production
DAO	Data Access Objects
DDE	Dynamic Data Exchange
DEMROP	Design Evaluation Method for the Recycling of Products
DFD	Design for Disassembly
DFE	Design for Environment
DFEE	Design for Energy Efficiency
DFMA	Design for Manufacture and Assembly
DFR	Design for Recycling (or Design for Recovery)
DFX	Design for "X"
DLR	German Aero Space Center
EAu	Environmental Auditing
ECDM	Environmentally Conscious Design and Manufacture
EHS	Environmental Health & Safety
EIA	Environmental Impact Assessment
EMA	Energy/Material Analysis
Embedding	Adding the source data for an item to a document; use the Paste command in a container application
EMS	Environmental Management Systems
EOL	End-of-life
EPA	Environmental Protection Agency (USA)
EPE	Environmental Performance Evaluation
EPP	Environmentally Preferred Product
EPR	Extended Producer Responsibility
ERA	Environmental Risk Assessment
ESD	Environmentally Sensitive (or Superior) Design
EUR	Estimated Ultimate Recovery
G8	Group of Eight (G8) consists of seven of the world's leading industrialized nations (Canada, France, Germany, Italy, Japan, the United Kingdom, the United States of America) and Russia

GEN	Global Eco-labeling Network
HID	High-Intensity Discharged (Lamp)
HTML	Hypertext Markup Language
IE	Industrial Ecology
IE	Industrial Estate
ISCM	Integrated Substance Chain Management
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCD	Life Cycle Design
LCE	Life Cycle Engineering
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
OECD	Organization for Economic Co-operation and Development
OLE	Object Linking and Embedding
OOP	Object Oriented Programming
PCB	Printed Circuit Board
PCBs	Polychlorinated Biphenyls
PCTs	Polychlorinated terphenyls
PLA	Product Line Analysis
PLCM	Product Life Cycle Management
POPs	Persistent Organic Pollutants
PP/P2	Pollution Prevention
RCC	Resource Conservation Challenge
ReOAT	Recycling-Oriented Assessment Tool
SFA	Substance Flow Analysis
SME	Small and Medium Enterprise
SQL	Structured Query Language
TCO	The Swedish Confederation of professional Employees
TQEM	Total Quality Environmental Management
UNEP	United Nations Environment Program
VDI	German Engineering Society
WWW	World Wide Web
WTO	World Trade Organization

DEFINITIONS

Part	One of the portions, equal or unequal, into which anything is divided, or regarded as divided.
Component	A part which combines with other parts to form a bigger part.
Joint Type	A connection mechanism between pairs of parts that are physically connected.
Sequence	The order in which parts/components are arranged.
Recycling Rate	Recycling Rate = Recycled Materials ÷ Overall Materials.
End-of-Life Cost	End-of-Life Cost = Recycling Profit – (Dismantling Cost, or Disposal Cost).
Recycling-Oriented Product Design	The average value of the twenty-two recycling-oriented product design categories (see **Section 4.8.7**).
Recycling Orientation	A short term for "recycling-oriented product design."

UNIT OF MEASURES

International System of Units (SI) is used in this dissertation. Therefore all measurements in this dissertation were calculated in ways of SI system, such as mass is measured in gram or kilogram, length is measured in cm, area is measured in cm^2, energy is measured in joule, and etc. Basic conversions of the SI units to the Imperial units used for different parameters are given as the short note below.

	SI Units	Imperial Units
Mass:	kilogram (kg)	= 2.205 pounds
Length:	meter (m)	= 3.281 feet
Area:	square centimetre (cm^2)	= 0.155 in^2
Volume:	cubic meter (m^3)	= 264.17 gallons
Pressure:	kilopascals (kPa)	= 0.145 pounds per square inch
Energy:	kilowatt-hour (kWh)	= 3,414.7 British Thermal Unit (Btu)
Power:	megawatt (MW)	= 1 x 10^6 J/s
Temperature:	ºC	= (ºF-32)/(1.8)

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Chapter 1

Introduction

> **"We live on one planet**, connected in a delicate, intricate web of ecological, social, economic and cultural relationships that shape our lives. Achieving sustainable development will require greater responsibility, for the ecosystems on which all life depends, for each other as a single human community, and for the generations that will follow our own."
> (Annan, 2005).

The development of a modern management tool with the capability and facilities for assessing the recycling-orientation of products at design stage based on a calculation mechanism taking into consideration product structure and components looks promising. However, in practice it is hard to narrow down this idea, which has broad theoretical backgrounds, to a solid model that comes close to achieving its best theoretical conception. In fact, when a new tool has been developed and released into the market, it functions and pretty well meets the requirements and challenges at a particular point in time. However, research and development as well as data collection are on going processes and hence new requirements and challenges are always present. It is therefore very important that beyond meeting its present chief objectives, any tool invented must provide the ability for upgrading. As an example for products development, Microsoft spent nearly three decades to improve their operation system (OS), from "QDOS 0.1" (history of the MS DOS, 1980) – to the current "Windows XP Professional" (64 bits-based, in 2005), which gives more possibility for running other applications (Lévénez, 2005). The software developed with this dissertation has the capacity to deliver the promising values. Feedbacks from users for improving the software are always necessary, although, it may require inventing new key functions, or upgrading the olds, e.g., database from time to time. The forecasting demands are given in the last chapter.

The dissertation framework introduces a new set of concerns for programming organs e.g., as recycling-oriented product design, hazardous materials, joint types, material cost, labor cost, recycling fractions costs, product's structure, product's end-of-life, and the communication between users and the software. This adds greatly to the complexity to the programming task. The software must manage all concerns in addition to computing results. It proposes a programming model based on gradual introduction of methodology used and implementation detail. It typically attempts to assist users to model the products to assess the recycling-orientation of product design by obtaining the profile of product data from two approaches: (1) Data of product profiles (secondary data) obtained directly from blueprints, descriptions, bills of materials e.g., type of materials, joint types; (2) Product disassembly (in most cases) – this approach is applied when secondary data are not available or not completed (dismantling and record the product profiles step by step).

Often, a disassembly/dismantling guidelines is missing from the product manual, leaves no clues for one who has no experience in disassembly/dismantling "where and how to start?", different non-professionals have different perspectives and use different disassembly/dismantling techniques, which lead to obtaining different results. This uncertainty can be resolved in two ways: (1) the product manufacturers provide the completed product profiles (mostly impossible, confidential data usually attached); (2) disassembly/dismantling the product (data extraction, when no data source available or not completed). Repetitive disassembly/dismantling can be made to ascertain the result – an average value (when the concerned product has more than one), it is scientifically approved when the majority gave the same trend (a small discrepancy is allowed).

After the product profiles is obtained the product model can be built by utilizing the software abilities, consequently the recycling-orientation of product design and other results can be calculated. This work is beneficial to those who need to know the recycling-orientation of product design e.g., designers, product engineers, and researchers; they can test their actual or conceptual models with their design parameters, variables and constraints, and predict the product properties. Moreover, when modifications are required this work shall serve as a prototype for future development. I hope that this work, among others, has contributed its quota towards organizational and industrial sustainability.

1.1 Background

Organizations[1] search and use the fittest plans and policies to achieve their prime objectives in a sustainable society. Decision making is central to all organizations and it is the starting point in any scheme of things. It is the most essential to all subsequent processes and activities. It is therefore important to make the best available decision in order to avoid consequent drawbacks – one must take information and relevant factors in both quantitative and qualitative into consideration. A number of management tools are used to identify problems in making decisions. A "strategic decision-making," was introduced and described by Hitt & Tyler (1991) in the strategic decision models by integrating different perspectives; two characteristics and one criteria were taken into account: (1) strategic choice (exclusives' characteristics); (2) rational normative criteria/objective criteria; and (3) external control (industrial characteristics) (see **Figure 1-1**).

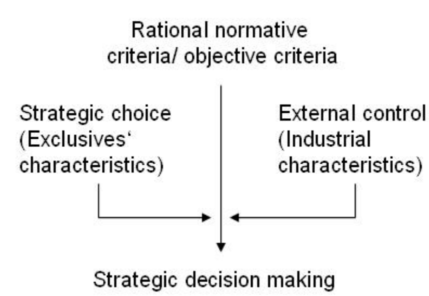


Figure 1-1: Three modes of strategic decision-making (source: Hitt, 1991).

Strategic decision making in products development in industrial sectors considers a number of factors e.g., a market competitiveness, global trends, society needs, organizational commitment, and legal aspects. The market competitiveness, global trends, and society needs has been considered as a "rational normative," which often follows a normative path, we cannot do much but increase our understanding and adaptation of organizations for win-win situations; organizational commitment has been

[1] The dissertation uses the term "organization" instead of "individual", "industry", "business", "company", "stake holder", "enterprise", "agency", "government", "non-government organization", "small and medium enterprise", etc.

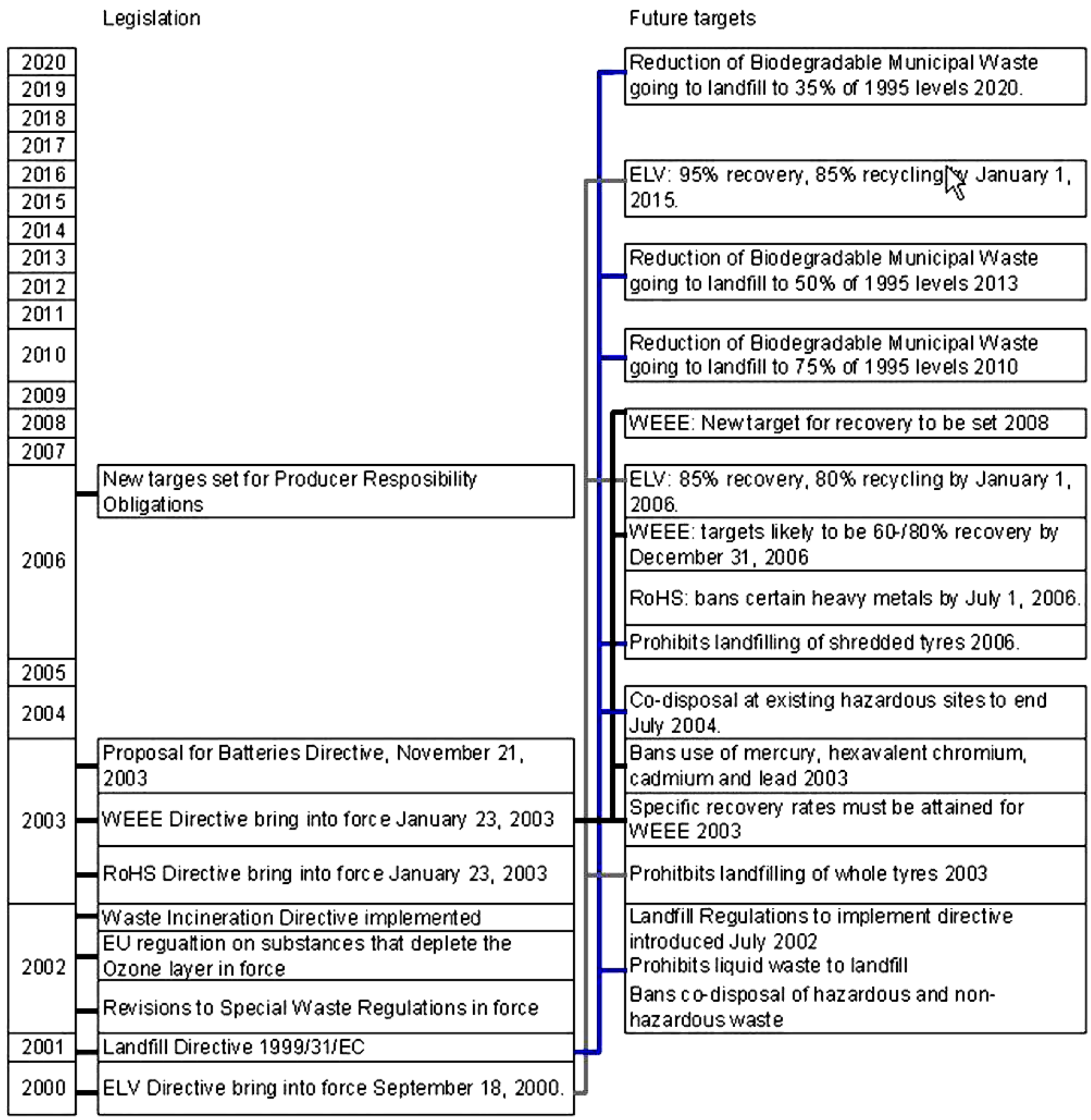
considered as a "strategic choice," which sets out internal standards to be followed; and the legal aspects has been considered as an "external control," which are beyond the authority of organization. These factors are the driving forces that help to accelerate, strengthen, and narrow down the strategic management resolutions, to answer the questions of: what to be focused on? how to make it? Commonly, we cannot understand and/or explain all the requirements for every organization because their status and conditions are differ from one to another, but we can identify general requirements, which apply to all organizations, i.e. the legal aspects.

With regard to accomplishing the aim of this dissertation to develop a methodology and invent a new tool for assessing the recycling-orientation of product design; the European products development and recycling related legislations have played an important role e.g., (1) recovery rate, reuse rate, and recycling rate; (2) recycling-oriented product design; and (3) restriction use of certain hazardous substances. No doubt, these issues have been taken into account in the dissertation as well. The main European products development and recycling related regulations are listed as follows.

1. Waste Electrical and Electronic Equipments (WEEE) Directive 2002/96/EC (2003), set out the percentage of recovery, reuse, and recycling goals, and bans certain substances.
2. Restriction of Hazardous Substances (RoHS) Directive 2002/95/EC (2003), set goals to decrease the used of heavy metals, and phase out heavy metals such as Pb, Hg, Cd, Cr6+, PBB, PBDE; some exemptions are given to soldering processes.
3. End-of-life Vehicle (ELV) Directive 2002/95/EC (2000), set out the percentage of recycling target goals for cars.
4. Energy-using Products (EuP) Directive 2005/32/EC (2005). It set eco-design requirements for energy-using products.
5. Integrated Product Policy (IPP), proposal of European Directive on integrated product policy; environmental performing improvement throughout product life-cycle (COM(2003) 302 final, 2003).

Other recycling related legislations and their targets for the period 2000-2020 are listed and arranged in the time series (see **Table 1-1**).

Table 1-1: EU recycling related legislations timeline 2000-2020



Legislations set out a number of targets and deadlines, and challenging to organizations. These, on the one hand, bring higher standards and enhance administrative systems for large enterprises; but on the other hand, they hinder or trouble SMEs, who are not yet ready, or unable to comply with the regulations. In developing countries, SMEs, often received the information too late for making their adjustments; and even if they have it in time, they have no such capacity to overcome limitations, e.g., the financial shortcomings; lack of human resources; no technology know-how; and weak infrastructure. Currently, most organizations in developing countries have no direct impacts from European products development and recycling related regulations, however they might already been encountered them indirectly, e.g., trading goods to countries where the regulations are enforced.

Looking at the whole world from history perspective, the world is shrinking daily by closer cooperation on political, communication, trading at international level and cooperation among international organizations. Any major change in any one country can affect others easily. In trading for example when one country imposes a new taxation system or adjusts import-export regulations, the impacts of these changes are felt in other countries.

In this era of “globalization,” and “internet,” things change faster than ever; to be sustained people have to be aware of global news besides being abreast with developments in their local areas. Sophisticate linkages between economic and trade bindings bring sophisticate changes.

Regarding the European products development and recycling related regulations, several methodologies are proposed and recommended not only to solve problems only at the end-of-pipe, but also to solve problems with respect to the whole life-spans of the product. This ranges from: (1) raw material extraction, (2) manufacture, (3) use, and (4) end-of-life phases (reuse, recycling, and disposal); or a so-called “cradle-to-gate,” “cradle-to-grave,” and “cradle-to-cradle” perspectives. The life-cycle thinking, life-cycle approach, and life-cycle assessment have been employed to solve problems on the issues of resources consumption; use of hazardous materials; wastes management; bottleneck identification; research development and design; evaluate existing products; and environmental cost allocation. They may lead to additional investment costs today, but in the long run the investment will bare benefits, e.g., the ability to define hotspots and solve them; reduce total energy and raw materials consumption; make cheaper the production costs, using secondary raw materials from take-back program or recycling materials; enables the designer, design products in such a way so as to facilitate disassembly, reuse, and recycling, especially for products that contained valuable materials i.e., electronic products.

Regarding products sustainability, three main factors are involved: cost; performance; and environment. These influenced by the decision-making process and are vital for organizational sustainability, (see **Figure 1-2**). Quantitative and qualitative analysis of these factors have to be made carefully, to find an optimal decision.

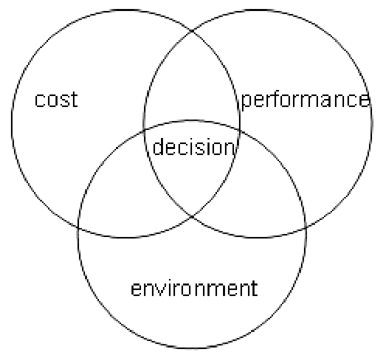


Figure 1-2: Business decision makers' integrate cost, performance, and environment consideration into product development, e.g., design for recycling.

The prime objective of this dissertation is to develop a methodology and invent tool for helping organizations to evaluate the recycling-orientation of product design. The tool is not designed for displaying or revealing overall product properties over the life-spans with all impacts categories. It does not take all inputs into account, but rather focuses on potential improvement of products regarding their end-of-life values.

In other words, it can be considered as a tool for designers. Designers should design a product and its life-cycle system so as to meet the requirements of environmental friendliness over the life-cycle of the product. Many researchers so far have pointed out the importance of design for reusing and recycling products effectively (Ertel, 1994). To assess overall product impacts over product life-cycle, consideration must be given to a wider dimension/spectrum of data inputs/outputs of materials and energy consumption during: raw material extraction, manufacturing, use, and end-of-life phases. The analysis is largely dependent on the goal and scope of the study, e.g., for a study focusing on three phases product life-span: (1) production, (2) use, and (3) recycling; the analysis can be made regardless of other phases (e.g., raw material extraction, disposal), hence the total life-cycle phases can be summarized as in **Figure 1-3**.

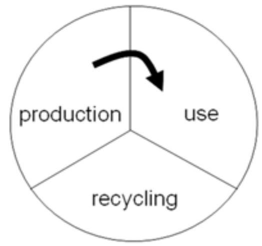
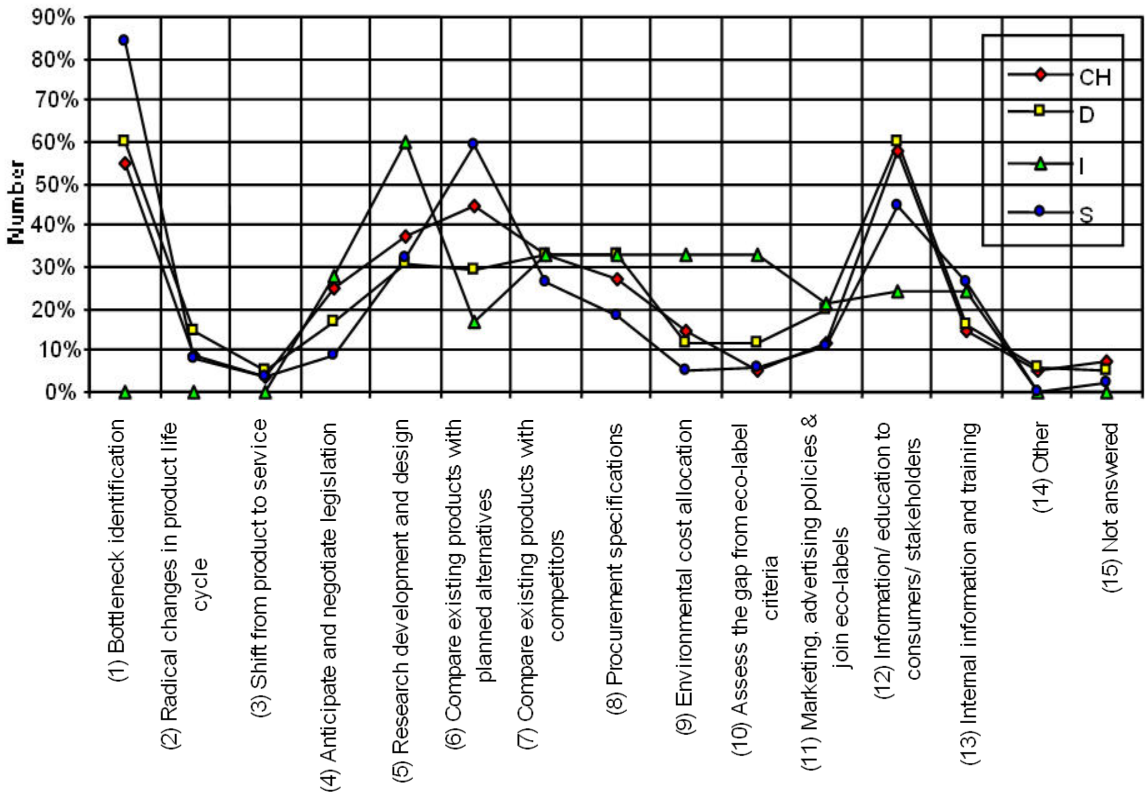


Figure 1-3: [Simple] product life-cycle (source: Jansen, 1995).

In order to give an impression about how a (new) tool can be beneficial to people who are using it? the results from the study of LCA tool is used for demonstration. This is to put the future benefits of my invented tool in perspective as LCA, is used as an example because my research employs several similar methodological/approach as LCA e.g., (1) data management; (2) set out criteria for rating; and (3) assessment to invented categories. The issues of (1) current situation of using life-cycle assessment; and (2) cost/benefit of carry out LCA, are described in the section below.

Frankl & Rubik (2000) carried out interesting questionnaires (1997), their research was focused on evaluating decision-making in the implementation of LCA in the European industry and business e.g., Germany, Italy, Sweden, and Switzerland. A total number of 1,625 questionnaires was mailed, and they received 382 feedbacks. Subsequently, they employed an analytical method for evaluating different target applications/issues. There were five parts consisting of 35 different questions in the questionnaire. However just two sets of relevant questions/results were addressed – the first question was, (1) What are the current applications of LCA in your companies? Companies were asked to tick up to four choices, (results were expressed in percent): (1) Bottleneck identification; (2) Radical changes in product life cycle; (3) Shift from product to service; (4) Anticipate and negotiate legislation; (5) Research development and design; (6) compare existing products with planned alternatives; (7) Compare existing products with competitors; (8) Procurement specifications; (9) Environmental cost allocation; (10) Assess the gap from eco-label criteria; (11) Marketing, advertising policies & join eco-labels; (12) Information/education to consumers/stakeholders; (13) Internal information and training; (14) others; and (15) Not answered.

Results (answers to the first question) from the study of Frankl & Rubik (2000) more or less pointed out the same trends in every country that LCA was mostly used for: bottleneck identification; research development and design; compare existing products with planned alternatives; and information/education to consumers/stakeholders. LCAs were mostly performed by the companies' internal teams (see **Figure 1-4**).



[up to four choices possible]

Figure 1-4: Current applications of LCA; 1997, (relative preference shares in % of companies using LCA in the countries (CH – Switzerland; D – Germany; I – Italy; S – Sweden) (source: modified from Frankl, 2000).

The second question was, What is the balance between costs and benefits of LCA? Several choices to answer this question were allowed, and the choices which given were: (1) Results can be immediately applied; (2) LCA benefits are long term ones; (3) Related to internal use of results; (4) Depending upon external use of results; (5) Others; and (6) Not answered. The results are illustrated in **Figure 1-5**.

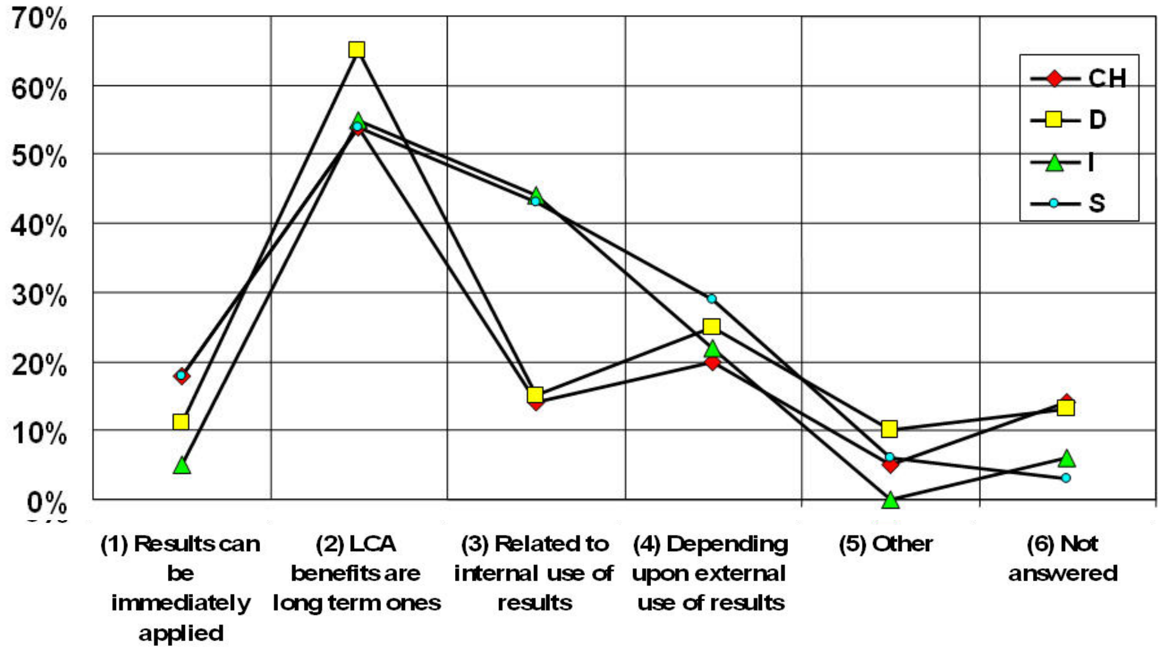


Figure 1-5: Benefits of LCA as they were perceived in companies in the different countries (CH – Switzerland; D – Germany; I – Italy; S – Sweden) (source: modified form Frankl, 2000).

There were three similar results in all countries and one big difference between two groups of countries. Companies in all countries did agree on the fact that results of LCA cannot easily be applied immediately and that benefits deriving from LCA are long-term. Italy and Sweden LCA (and its benefits) is perceived mostly as an internal tool whereas in Switzerland and Germany there is a stronger focus on the external use of LCA.

The dissertation was expected to solve problems on: (1) Bottleneck identification, (2) Research and development in products design, and benchmarking. It proposed its findings for extensive use and integration with tools such as LCA. Its benefits are expected to strive the similar goals of the LCA's applications but on different life-cycle phases.

1.2 Summary of Research

1.2.1 The Problem

Software developers use a variety of algorithms in building various applications to solve problems such as: operation systems, applications development, multi-users database, the Internet, games, modeling, sciences, mathematics, economics, biology, chemistry, equations, atom-molecules, flood simulation, earthquake simulation, earth formation, universe formation, etc. These wide spectrums of software applications that employ algorithms are mostly available on the market, but some are not for sales but rather serve as prototype or restricted for in-house use purposes.

Several product/process development and recycling-related software applications are available in the market e.g., "Umberto" is used for material flow analysis, cost accounting, and environment impacts assessment; "DFMA" is used for product manufacture and assembly analysis and concurrent costing. Both software, have their own strengths and specific functions on product or project modeling; however they cannot be used interchangeably because their core abilities are not the same. In short, individual software contains strengths in the area for which it is designed, at the same time contains weaknesses and limitations in other areas.

Taking "Word[2]" and "Excel[3]" as examples, Word is mainly used for composing documents/reports, but in working with spreadsheets for statistics – Excel is more practical. It would not be convenienced at all, to use Excel for composing a dissertation. A combined use of softwares can fulfil, offset limitations, and decouple the subjective goals. In producing a complex and long document (e.g., dissertation) with tables, figures, common tools such as "Word," "Macros Add-in," "Excel," "PowerPoint[4]," "Drawing," and "Screen Capture" are usually needed to supplement one another. In programming a new software that deal with database management and reporting, basically, "Visual

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[2] Word: a software for word processing by Microsoft Corporation.
[3] Excel: a software for spreadsheet by Microsoft Corporation.
[4] PowerPoint: a software for presentation by Microsoft Corporation.

Basic[5]," "Access[6]," and "Crystal Reports[7]" are needed in combination. There are a lot more combinational choices depending upon individual preference.

This dissertation is focusing on developing a software for the determination of the recycling-orientation of products at design stage. There are few softwares (expertise in this area), already available in the market. This research will resolve problematic issues associated with the existing softwares. These problems are listed as the following:

1. Missing a particular function (which users are specifically needed)
2. Fixed database (users cannot make any change)
3. Complex algorithms (not user-friendly)
4. Design for high-end (advanced users only)
5. Results are difficult to interpret (no basic knowledge/training)
6. Pricey (unaffordable to students)

Common users pay much attention on price first apart from other softwares attributes e.g., functions, database. In general, commercial recycling-related and product development software, "professional version" is unaffordable for non-professional or beginners. This is because recycling-related and product development software are relatively new (new invention usually expensive), expensive database. They provide special functions and in-depth analysis with large database serving for projects raging from basic-to-highly-sophisticate. Software "education version", the price is still a way more expensive for students to afford. Whereby a free "trial version" usually does not delivers full functions/abilities, or it expires in a couple of days after it is downloaded/installed. Large enterprises, organizations, institutes, companies, and industries are the real target customers of big software companies, because they have a buying-power, and have real demand.

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[5] Visual Basic: a software for programming by Microsoft Corporation.
[6] Access: a software for database management by Microsoft Corporation.
[7] Crystal reports: a software for report making, a third party package that is included with Visual Basic.

1.2.2 The Solution

My solution to the previous problems takes a radically different approach than current algorithms. Instead of striving to encapsulate many different features in a monolithic manner, I propose a lightweight algorithm architecture that enables users to pick and choose the features they need. I call this architecture as a "Recycling-Oriented Assessment Tool," or ReOAT. ReOAT provides a new algorithm architecture that solve problem of traditional algorithm architectures through a combination of ideas from object systems, adaptive software models, and composition of software demands. This yields an alternative that can be integrated into object-oriented applications, tailored to specific applications and grew to accommodate new features. Adopting an object-oriented architectural style requires looking at the big picture through the object lens. ReOAT fully embraces object-orientation; one of the key characteristics of ReOAT is that it applies techniques typical of object systems to solve product assessment and management problems. It reduces the impedance mismatch between the provider of algorithm functionality and application objectives. Software users can use, customize, and present results by means of reports.

1.2.3 The Method

Engineering disciplines hide behind the large bodies of theory accumulated over long periods of time e.g., civil engineers plan, design, and supervise the construction of facilities such as high-rise buildings, airports, water treatment centers, industrial manufacturing and processing facilities, sanitation plants, meeting the challenges of pollution, traffic congestion, drinking water and energy needs, urban redevelopment and community planning. The origins of civil engineering date back to ancient Egypt – plan to build, and the use of mathematics to achieve a desired result instead of building haphazardly. But software engineering has a much shorter history than most engineering fields. It is an exceptionally fast-moving field, where knowledge is subject to rapid obsolescence and ideas progress swiftly from research to practice. As a result, software engineers do not “calculate” software designs; instead they follow guidelines and good examples of working designs and architectures that help to make successful decisions, the “state-of-the-art” (Nanoescu, 1997). Therefore, in the context of software engineering, communicating experience, insight, and providing good examples are important tasks.

There are several weaknesses with traditional structured programming where data is stored separately from procedural code. Any code that is written as structured code is not modular. It is possible for data to be modified without the developer’s knowledge because data elements can be accessed from any code. It results in runtime errors that are very difficult to debug. Object Oriented Programming (OOP) solves these problems. It packages data, into a single unit called an object. An object’s data can be hidden to prevent unauthorized modification; the object surfaces a set of public methods to operate on this data, as a so-called “encapsulation.” As implementation details are separated from the interface, the underlying programming logic can be changed at a later time without breaking code (that calls the object). Developers can reuse code and data together through OOP inheritance; by inheriting from predefined objects, the rapid construction of complex applications can be made (Developer Fusion, 2003).

My research provides a new way of building and implementing object-oriented systems and applications. I choose design decisions and components that are compatible to built-in objects as well as new objects corresponding to build the chosen architecture. Building the new architecture involves (1) Translating the abstractions into a programming language; (2) Building components that provide advanced features, as well as (3) Implementing with different requirements. Since writing new code always has the potential for incorporating bugs, reusing tested code minimizes the chances of additional bugs. Architecture is not the end product; rather it provides a holistic view. The following basic structures (objects) have been linked to the architecture:

1. Visual Basic, Object-Oriented Programming (OOP)
2. Dynamic Data Exchange (DDE), techniques for communicating with other windows programs

3. Object Linking and Embedding (OLE), a compound document is something like a display desktop that can contain visual and information objects of all kinds
4. ActiveX Controls, by actions of mouse/keyboard – event/display change
5. Database, as references and basis for calculation

Database has been collected and elaborated (both primary and secondary data quality); they are valid and up-to-date, which come from various sources such as:

- Test-data (primary data), from laboratory tests: tools, joint types, disassembly time
- Material-data (secondary data), from research and literature reviews: type of materials, hazardous materials
- Cost-data (secondary data), from recycling-related business, personal contacts, research and literature reviews: recycling cost, disposal cost, disassembly cost
- Control-data (secondary data), from European Unions, international levels: certain directives/laws/standards/regulations (banned of hazardous materials, recycling related, % target goals)
- Custom-data (new data), add into the software by users (products profiles, projects information)

This design architecture was constructed by taking ability to be customized & flexibility as chief considerations (further development, modifying and upgrading are possible); it now can be seen as a new tool. In summary, the tool consists of inputs (product profiles, database) and mechanism characteristics (data transfers between objects), which will be interpreted and used by control algorithms (assigned mathematical prescriptions), that yields outputs (product performance, recycling-orientation of product design, reports) (see **Figure 1-6**). The ideal solution tool has been brought into life.

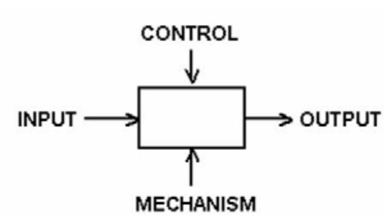


Figure 1-6: Solution tool.

1.3 Dissertation Structure

The dissertation is structured as follows; **Chapter 2** presents a comprehensive overview of “related research” in the field of products development, products recycling, and environmental impacts during products life-spans. The main characteristics and usages of the existing researches for quick comparison. **Chapter 3** presents a comprehensive overview of “related software” in the field of products development, products recycling, and environmental impacts during products life-spans; describes related software characteristics and analyzes their advantages and limitations. The comparison between ReOAT and other related softwares is provided. Later on, the related research and related software important information, approach, and idea of design considerations are connected and integrated, which are described in detail in **Chapter 4**, and thus used for building the prototype model. In **Chapter 5**, the “Recycling-Oriented Assessment Tool” ReOAT, is built from eight models, which are explained in details with respect to its synthesis algorithms; features; and functions architectures, from element to element, that are used for the assessment of the recycling-orientation of product design. Finally, **Chapter 6** concludes the dissertation, points out open issues and future research directions in the field.

Chapter 2

Related Research

> "**Sustainability** is… a possible way of living or being in which individuals, firms, governments, and other institutions act responsibly in taking care of the future as if it belonged to them today, in equitably sharing the ecological resources on which the survival of human and other species depends, and in assuring that all who live today and in the future will be able to flourish, that is, to satisfy their needs and human aspirations." (Ehrenfeld, 1997).

2.1 Introduction

This chapter provides a comprehensive overview of related research topics in the field of recycling-orientation of product design. Searching for potential information that could be employed. Scope of interests is ranging from in-house (internal) researches/tools to international researches/tools. This chapter tends to collect relevant descriptive information on the widest perspectives as concise as possible. Consequently, research topics are gradually introduced. After being highlighted and explained the relevant issues (principle/methodology) that could be further adopted and formulated into the dissertation assumptions for inventing a new tool are dealt with. At the end of this chapter, the related researches are reviewed and summarized.

In European environmental related regulations, almost all environmental (economic, and society) management tools and strategies, are being used and recommended as the basis requirements to: (1) Improve as such situations/conditions to be better off; (2) Combat environmental (economic, and society) problems; and (3) Enable organizations to compliance with standards and regulations, which can be done by one or more ways.

Several types of environmental management tool are invented and are being used according to organizational needs. However, it can be puzzling in trying to answer the questions: What tools are available and being used by others? What can they do? Which one is the most suitable for the organizational goals? because there are a number of tools that have similar characteristics. Answering on which one is the most appropriate, the answer has to be considered case by case regarding individual organizational characteristics. To giving the idea for example, what environmental management tools are being used and what are their functions, short lists have been made, as follows:

1. Cleaner Technology. Cleaner Technology is a manufacturing process which by its nature or intrinsically: reduces (1) effluents, (2) wastes production; maximizes (3) products quality; (4) use of raw materials/energy and other inputs. On the other hand it may be used as a comparative term (ICETT, 1998).
2. Design for X (DFX). "DFX is a design for product evolution, where X can represent manufacturability, testability, reliability, or other "downstream" design considerations" (Allenby, 1991).
3. Industrial Ecology (IE). "IE is based upon a straightforward analogy with natural ecological systems. The system structure of a natural ecology and the structure of an industrial system, or an economic system, are extremely similar" (Frosch, 1992).
4. Integrated Substance Chain Management (ISCM). ISCM uses essentially the same algorithm as the Inventory stage of LCA in quantifying all materials and energy that enter or exit the system under study.
5. Life Cycle Assessment (LCA). LCA identifies resources used and wastes generation to the environmental compartments (air, water, soil), over specific goods or services life-spans.
6. Life-cycle Thinking. Life-cycle Thinking relates to the roles such thinking of the whole chain of production as well as product composition, and to raw materials extraction. From various actors e.g., manufacturers, trade groups, and consumers (Heiskennen, 2001).
7. Energy/Material Assessment (EMA). EMA uses essentially the same algorithm as the Inventory stage of LCA in quantifying all materials and energy that enter or exit the system under study.

8. Environmental Risk Assessment (ERA). ERA covers a wide range of applications, e.g., human/ecological risk assessment at specific points, areas.
9. Environmental Impact Assessment (EIA). EIA is used to assess future changes to the environment at specific sites of construction projects e.g., power plants, highways, industrial sites.
10. Environmental Auditing (EAu). EAu its origins lie in physical inspections of sites to check legal compliances and to identify major risks and liabilities.
11. Environmental Performance Evaluation (EPE). EPE is an internal tool for organizations, provides reliable management information/strategies ensuring the organizations meeting their environmental objectives.
12. Substance Flow Analysis (SFA). SFA balances and analyzes inflows/outflows of one particular substance through the material economy (usually in large scale).
13. Total Quality Environmental Management (TQEM). "TQEM is a method involving the improvement of product quality through incremental improvements in both products and processes. …extends the principles of quality management to include manufacturing practices and processes that affect environmental quality" (Florida, 1996).
14. Product Line Analysis (PLA). PLA investigates the impacts on society and economy. PLA can be said to be a tool that combines an environmental LCA with social and economic LCAs.

These aforementioned tools are designed and used to investigate, understand, moderate, and tackle specific environmental (as well as, economical, and societal) problems. They are classified by types of their ultimate functions and the final works they can do, which can be used as a standalone entry or in combination with others to serve and fulfil the specific needs. Essentially, the classification of tools type is based on the tool characteristics e.g., (1) Valuation method, (2) Assessment method, (3) Interpretation, and (4) Results implementation. The accuracy of results depends largely on type/quality/quantity of data and the method of implementation. Imagine you have one set of data which mostly has infinite ways of using (see **Figure 2-1**).

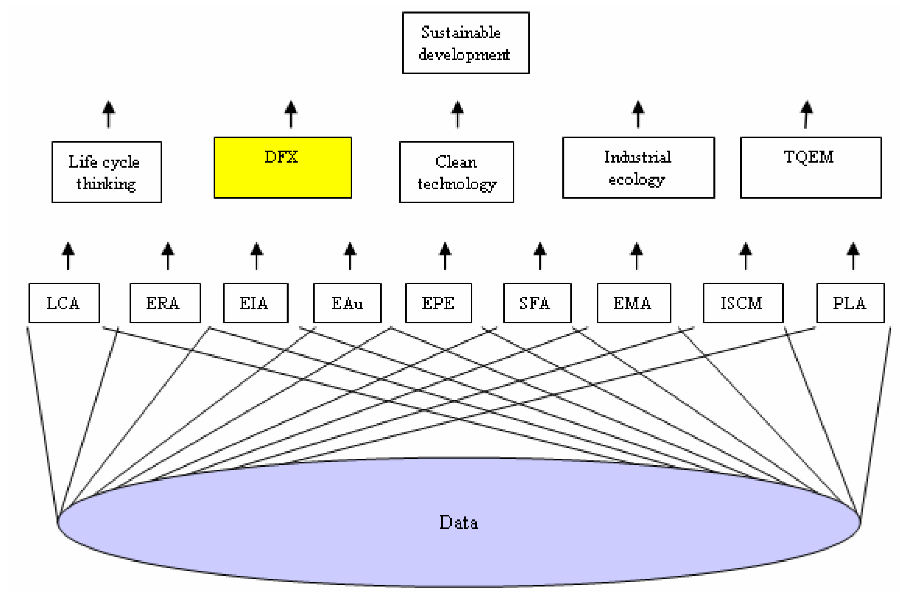


Figure 2-1: Same data can be used by different tools for achieving sustainable development.

Different tools use different assumptions treat the same data in different ways and give different results. When a new method, assumption, hypothesis, theory and implementation can be formulated differently or a completely new idea is introduced, which results in a better output quality, then there always be a room for a new tool. The fitter tools will gradual be more accepted in the system, and only the fittest tools will remain. It does not mean that the fittest survival tools should be only one tool/method; as the diversity of nature. The central objective of most tools is mainly for "Sustainability" and achieving "Sustainable Development," (SD).

The work proposed in this dissertation does not take every tool (aspect/concept) displayed in **Figure 2-1** into account, but rather focused on the study of recycling-oriented product design, which corresponds to certain related research areas. The related research topics and their issues that are relevant to this work are discussed in the following sections, which include:

1. 3R. 3R (reduction, reuse, recycle), the environmental policy which focus almost naturally coincides with Eco-efficiency strategies (Bleischwitz, 2002).
2. Industrial Ecology (IE). "IE is the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the

environment, and of the influences of economic, political, regulatory and social factors of the flow, use and transformation of resources” (White, 1994).

3. Product Design. Product design (modern) is always trying to get a better and cheaper product out in less time. It is typically multi-disciplinary and multi-leveled approach to decrease lead-time and cost, and increase quality (Bras, 1997).
4. Design for Manufacture and Assembly (DFM/A). DFM/A fundamentally considers on the basis goals of increasing the feasibility of manufacturing, and assembling on lowering the production cost.
5. Design for Recycling (DFR). DFR is a “simultaneous” planning for post-life use of the product in the early stages of design, i.e., design for product retirement (DFPR) is advanced planning for effective disassembly, reuse, and recycling of a product in the early stages of its design (Ishii, 1996).
6. Design for Environment (DFE). “DFE is an integral component of the “design for X” paradigm, covers a wide range of product development activities including such tasks as choosing materials, examining the product usage phase to reduce environmental impact, designing for energy efficiency, minimizing industrial residues during manufacturing, designing for recycling” (Ishii, 1998).
7. Eco-efficiency. “Eco-efficiency promoting material use intensity in production processes to achieve maximal production, as well as integrated production that yields several products of commercial value from one production process” (Fussler, 1996). The surge of interest in “lean production” has also served to promote materials use efficiency (Romm, 1994).
8. Eco-design. Eco-design (product design for sustainability) reduces the ecological footprint on the Earth’s natural resources; products that are lighter, smaller, more durable, more versatile, human-powered, reparable, recyclable or reusable (US OTA, 1992; van Weenen, 1997).
9. Life Cycle Assessment (LCA). LCA enables the evaluation of the environmental impacts of products and processes during their life cycles, from selection of the raw materials through manufacture and use to disposal and waste management

(Gyll, 1996).

10. Integrated Product Policy (IPP). IPP seeks to stimulate demand for greener products and to promote greener design and production (COM(2003) 302 final, 2003).
11. Trend towards Industrial Sustainability. Trend towards Industrial Sustainability focuses more on prevention, innovation and structural change of ecologically sound industrial development by using cleaner technology, recycling, and renewable resources. It requires a conversation of the ecological and the economy, a re-orientation of environmental policy, and a replenishment of economic policy (Simonis, 2005; Paulus, 1986).

In total, these broad issues and concepts proposed point out in the same direction to achieve better harmony between policy, economy and ecology. These are the relevant arenas of this dissertation, and are particularly brought into focus. In this chapter, First, I am going to present some practical evidence on the relationship among, (1) control policy, (2) economic structure, and (3) environmental impacts. Second, I shall point out some deficiencies of environmental related concerns especially on the recycling-orientation of product development. Third, I shall put forward ideas obtained from the related researches on integrating recycling-oriented considerations into product design. I will proceed with preliminary ideas from my hypothesis to build up the recycling-oriented assessment tool.

2.2 3R

Reduce, reuse, and recycle the "3R," is a simple policy to minimize resource consumption. This well-known policy is applied by most forefront industries through out the world from the past centuries. Because of rapid consumptions of global resources, and population explosion in developing countries, the efforts to combat environmental problems for global sustainable development has arisen worldwide. Recently in June 2004 issues of CO_2 emission, resource depletion and 3Rs have been highlighted by G8 summit, at Sea Island, the USA. Following this, the 3R Initiative was commissioned at the ministerial conference, in April 2005, Tokyo, Japan for the promotion of the 3Rs.

2.2.1 Background of the 3R Initiative

The 3R Initiative was endorsed at the G8 Summit held in June 2004 at Sea Island, the USA (see **Figure 2-2**). It was decided to officially launch the 3R Initiative at a ministerial meeting in Tokyo, Japan on 28-30 April 2005, with the participation of twenty countries: Brazil, Canada, China, France, Germany, Indonesia, Italy, Japan, Malaysia, Mexico, the Philippines, the Republic of Korea, Russia, Singapore, South Africa, Thailand, the United Kingdom, the United States of America, Vietnam and the European Commission; and four international organizations: UNEP, OECD, the Secretariat of the Basel Convention and the League of Arab States. The 3Rs was expected to be discussed substantially at the G8 Summit held in July 2005, at Gleneagles, UK (3R Initiative, 2005).

Figure 2-2: Sea Island, G8 Summit 2004 (source: 3R Initiative, 2005b).

2.2.2 Objectives of the 3R Initiative

The 3R Action Plan set forth the following five points to be pursued through the 3R Initiative (3R Initiative, 2005):

1. Formulation and implementation of visions and/or strategies leading to a sound material-cycle society (see **Figure 2-3**).
2. Reduction of barriers to the international flow of goods and materials for recycling and remanufacturing, recycled and remanufactured products, and cleaner, more efficient technologies, consistent with existing environmental and trade obligations and frameworks.
3. Cooperation between developed and developing countries in such areas as capacity building, raising public awareness, human resource development and implementation of recycling projects.
4. Cooperation among various stakeholders (central/local governments, the private sector, NGOs and communities), including voluntary and market-based activities.
5. Promotion of science and technology suitable for the 3Rs.

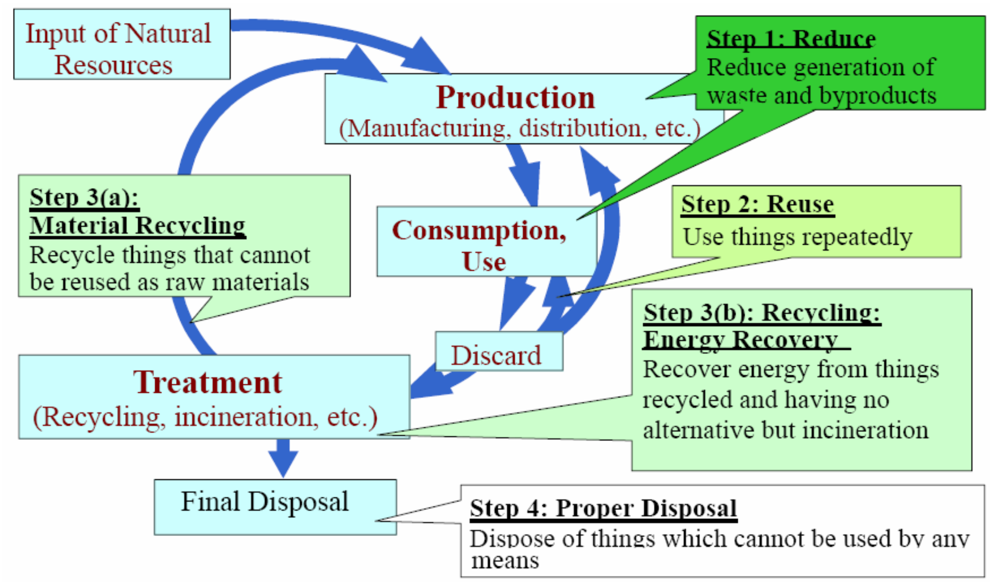


Figure 2-3: Concept of the 3Rs in a Sound Material-Cycle Society (source: 3R Initiative, 2005a).

2.2.3 3R Initiative from Participants' Countries

In the Ministerial Conference on the 3R Initiative, April 2005, Tokyo, Japan, participants reiterated their commitment to Agenda 21 (in 1992) and the importance of the fulfilment of the Johannesburg Plan of Implementation of the World Summit on Sustainable Development (3R Initiative, 2005). With regards to the commitment to the 3R Initiative, responses are obtained from all participants (developing and developed countries). Responses in recycling related issues from five countries e.g., (1) China [with the largest population, 1.3 billion which is one-fifth of the world population (CPIRC; UCBPD, 2005)], (2) Germany, (3) Japan, (4) Thailand, and (5) The USA are selected as the representatives for other countries, and are summarized in the following sectors.

2.2.3.1 China

The government is seeking to establish a circular economy,[8] through a legislative framework and trials at local levels e.g., (1) Law of prevention and control of environmental pollution by solid wastes, (2) Developing basic law and the promotion of circular economy (Ren, 2005). The circular economy policy is incorporated in China's eleventh 5-year national development plan. Eco-industrial parks, energy-saving buildings, and certification for cleaner production had been introduced.

2.2.3.2 Germany

German 3Rs policy has stabilized waste volumes over the last 15 years, and has increased recycling rates (Jaron, 2005). This has been supported by regulations e.g., (1) End-of-life vehicle act (Directive 2000/53/EC, 2000; Federal Ministry, 2002); (2) Act on the disposal of waste electrical and electronic equipment [Directive 2003/108/EC, 2003; (3) Directive 2002/96/EC (WEEE); (4) Directive 2002/95/EC (RoHS), 2002]; (5) Battery ordinance (COM(2003) 723 final, 2003); (6) Ordinance on bio-wastes, packaging ordinance (Packaging Ordinance, 2002); (7) Ordinance on the management of waste wood (Waste Wood Ordinance, 2002); (8) Ordinance on commercial waste (Commercial Wastes Ordinance, 2002); (9) Landfill ordinance (Landfill Ordinance, 2002); (10) Directive on the prohibition of PCBs and PCTs (Directive 96/59/EC, 1996); (11) EU directive on Persistent Organic Pollutants (POPs) (Directive 79/117/EEC, 2004) aiming towards the development of a closed-substance circle economy. LCA of environmental impacts of products on their total useful life is used as a basis for these regulations. One example of this is the compulsory deposits on drinks packaging, which has promoted their reuse (Report, 2003). Since 2005, landfilling is only permitted after pre-treatment. This reduces CO_2 emissions. Germany aims to end landfilling by 2020 (Directive 1999/31/EC, 1999).

[8] Circular economy refers to an economy that features closed-circuited material flow. It is an economic model where materials and energies are utilized in an aggressive, closed-circuited way, which features low emission or even zero emission. Protection and exploitation of biological resources are the key foundation for the development of a circular economy (UNEP, 2004).

2.2.3.3 Japan

The government aims to realize a zero-waste society in Japan based on the quantitative targets and further 3R actions by (1) Enactment of the fundamental law for establishing a sound material-cycle society (Fundamental Law for Establishing a Sound Material-Cycle, 2000; UN, 2004); (2) Formulation of basic policies based on the law and setting up targets for waste reduction (1997-2010) (Morishita, 2005); (3) Law for effective utilization of resources (1991); (4) Container and packaging recycling law (1995), (5) Home appliance recycling law (1998); (6) Construction material recycling law (2000); (7) Food waste recycling law (2000); (8) End-of-life vehicles recycling law (2002); (9) Global ecolabeling network (GEN) (GEN, 2005); (10) 3R Initiative (2005); and (11) Disseminate its experience to the international community. Japan also supports developing countries' capacity development, and collaboration with international organizations, e.g., G8, Asian network, and international green purchase network (Morishita, 2005).

2.2.3.4 Thailand

The government has developed a national integrated waste management plan. It has also taken measures to prevent the export of waste to Thailand. Many 3R projects are being implemented, including (1) Government green procurement; (2) Industries waste exchange program, over 400 industries registered; (3) Tax incentives, encourage the recycling of lead-acid batteries at a rate of 84%; (4) Green label scheme, take-back program on end-of-life products; and (5) Thailand green purchasing network (Thongkaimook, 2005). Through technology and knowledge transfer relating to 3Rs the green product and services, e-waste management, life-cycle assessment, eco-design, eco-efficiency, cleaner production, recycling and green material technology has been initiated in cooperation with other countries.

2.2.3.5 The United States of America

US EPA develops a framework for increasing the rate of municipal solid waste recycling to 35%, targeted waste streams include paper, organics, and packaging/containers. The 3R is used for (1) Promote environmentally-smart design of electronics, container/packaging carpets, paints, tires to prolong their life and promote reuse and recycling; and (2) Resource conservation challenge (RCC) combines many US EPA programs and partners by preventing pollution and promoting recycling and reuse of materials in innovative ways to conserve nation's resources and use material effectively (Leith, 2005). The 3Rs reflect life cycle concepts, by encouraging prudent design, purchase, and use of products, environmentally sound recycling and manufacturing. Reliance will be on markets rather than over-regulation. Regulations should permit and support innovation.

2.2.4 Summary of 3R

During the past 20 years the World's resource consumption has been increasing rapidly. In the 1980s, the OECD countries' efforts at promotion the 3Rs have been strengthened and the recognition of waste minimization has been increased. Improvement in the efficiency level through technological developments and structural changes in the economy has been offset by an even higher increase in absolute production levels throughout the world, and the environmental pressure posed by the utilization of resources is even greater (3R Initiative, 2005). It is necessary to bring down environmental pressures regarding resource utilization to sustainable levels. Responses from participant countries described in the preceding sections, show the consensus for revitalizing and emphasizing the concept of reduce, reuse, and recycle. The deliberations of 3Rs for sustainable development is obviously very demanding concept in terms of implementation within the participating countries.

2.3 Industrial Ecology

Industrial Ecology is...? Industrial Metabolism is…? Industrial Symbiosis is…? and other similar buzzwords relevant to this area are the terms that common people hardly distinguish and clarify. These concepts are relatively new and most of them still have to be proven. However, experts working in the area have defined: (1) Industrial ecology; (2) Industrial metabolism; and (3) Industrial symbiosis, as:

"Industrial Ecology is …a new way to design policy & socio-economic systems based on ecological features: Products/service systems; Urban structures and industrial symbioses; Material and energy policies. …A new paradigm? Dissolving the contradictions of modern industrial societies; creating new social structures" (Ehrenfeld, 2003).

"Industrial Metabolism is …the whole of the materials and energy flows going through the industrial system. It is studied through an essentially analytical and descriptive approach (basically an application of materials-balance principles), aimed at understanding the circulation of the materials and energy flows (and stocks) linked to human activity, from their initial extraction to their inevitable reintegration sooner or later, into the overall biochemical cycles" (Ayres, 1994).

"Industrial Symbiosis is …a group of industries work in collaboration through exchanges to reduce natural resource consumption and pollution. Industrial symbiosis involves linking companies so that the by-product of one company may be used as a feedstock to the other company, with drastically elimination of wastes. There is also energy cascading, this involves the use of residual heat in liquids or steam from one process to provide heating, cooling or pressure for another process" (Industrial Symbiosis, 2005).

2.3.1 Industrial Symbiosis in Denmark

In Denmark, the city “Kalundborg” (located 100 km west of Copenhagen) is one of the best examples that can explain the idea behind *industrial symbiosis*. This concept evolved over the past three decades (Industrial Symbiosis, 2005). The criteria for industrial symbiosis are:

1. *The companies must fit each other*. One company’s residual products must take the place of another company’s raw material, diversity within the local industrial structure is very important; large number of companies give more chance of matching demanders to potential suppliers.
2. *The companies must be located near each other*. Transportation cost play a very important role to realize the exchange of material or energy. The geographical distance is the most important parameter when energy is exchanged between the companies e.g. in *Kalundborg*. Other by-products can be transported to advantage over larger distances.
3. *There must be openness between the companies*. Today the basis of the symbiotic co-operation of Kalundborg is openness, communication, and mutual *trust* between the partners; open relations in a small community.

The exchange of residual products between the companies is laid out in the diagram (see **Figure 2-4**). All projects are environmentally and financially sustainable.

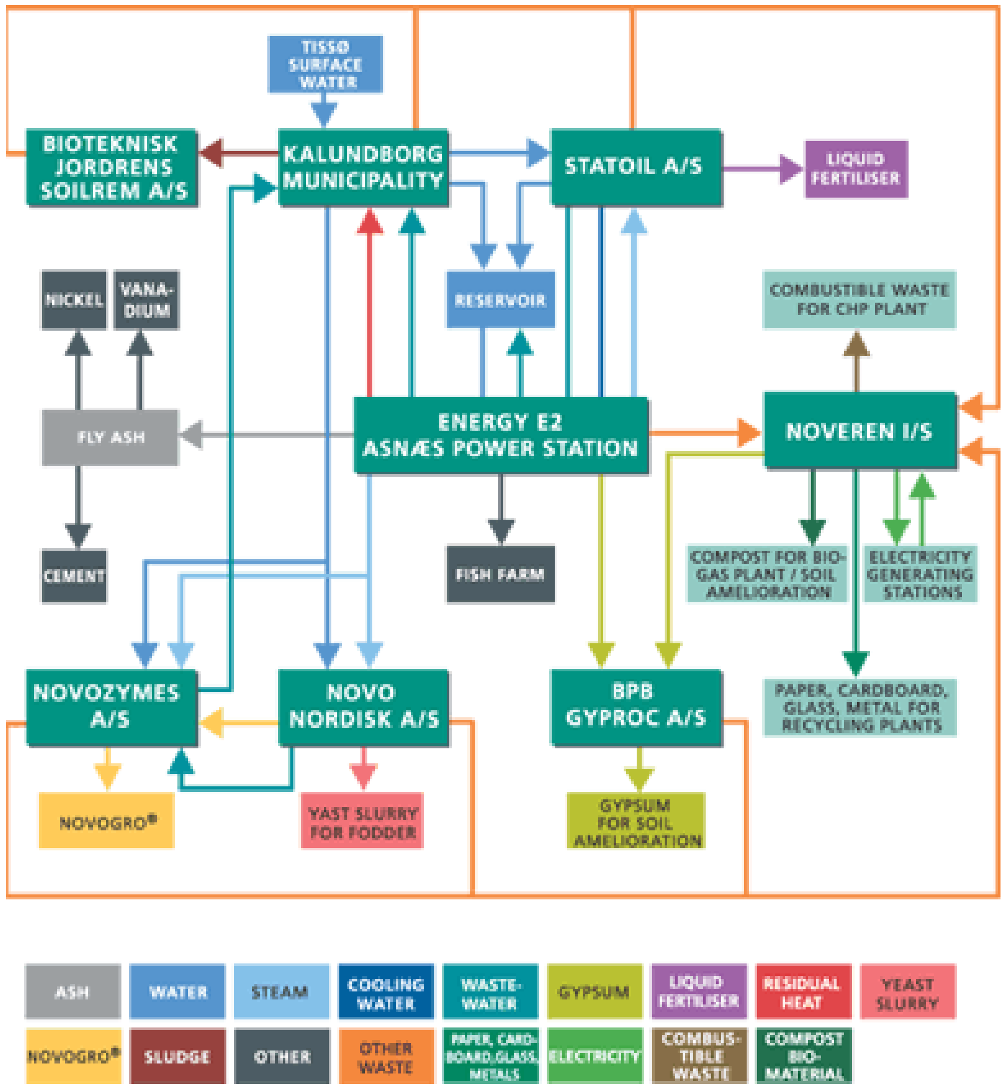


Figure 2-4: Industrial symbiosis at Kalundborg – material and energy flow (source: Industrial Symbiosis, 2005).

The Industrial Symbiosis of Kalundborg is built as a *network* of co-operation among six main companies e.g., (1) Energy E2 Asaes Power Station; (2) The plasterboard factory BPB Gyproc A/S; (3) The pharmaceutical plant Novo Nordisk A/S; (4) The enzyme producer Novozymes A/S; (5) The oil refinery Statoil A/S; (6) Bioteknisk Jordrens Soilrem A/S; one waste handling company (7) Noveren I/S; and (8) The Municipality of Kalundborg (Garner, 1995). The collaborating partners not only exchange wastes to reduce raw material extraction costs, but also commercially sustain by the reduction of emissions and wastes treatment costs.

2.3.2 The Development of Industrial Ecology

Industrial Ecology draws on nature as a metaphor for sustainability. Fundamental research in industrial ecology focuses on the long-term relationships between (1) Materials and energy use, (2) The environment and human health, and (3) Economic well-being (Thomas, 2003). It uses ecological rules (analogies) to design technology and infrastructure and is still an emerging concept with much to be proven. It underpins other systems of sustainability practice. Today, industrial ecology is being pursued with unprecedented vigour. It is gaining recognition not only in business communities, but also in academic and government circles. In 1997, the Journal of Industrial Ecology was launched, and in early 2001, the International Society for Industrial Ecology was founded (Journal of Industrial Ecology, 2004).

2.3.3 Eco-Industrial Estate and Network in Thailand

The Eco-Industrial Estate (EIE) concept is formulated first by the Industrial Estate Authority of Thailand (IEAT) in collaboration with the German Technical Cooperation (GTZ). EIE is to a group of productions and services that are oriented toward raising the standards of environmental quality and business performance, at the same time maintaining good relationship with neighbouring communities through collaboration on natural resource and environmental management. The Thai's industrial estates are mapped out and displayed in **Figure 2-5**.

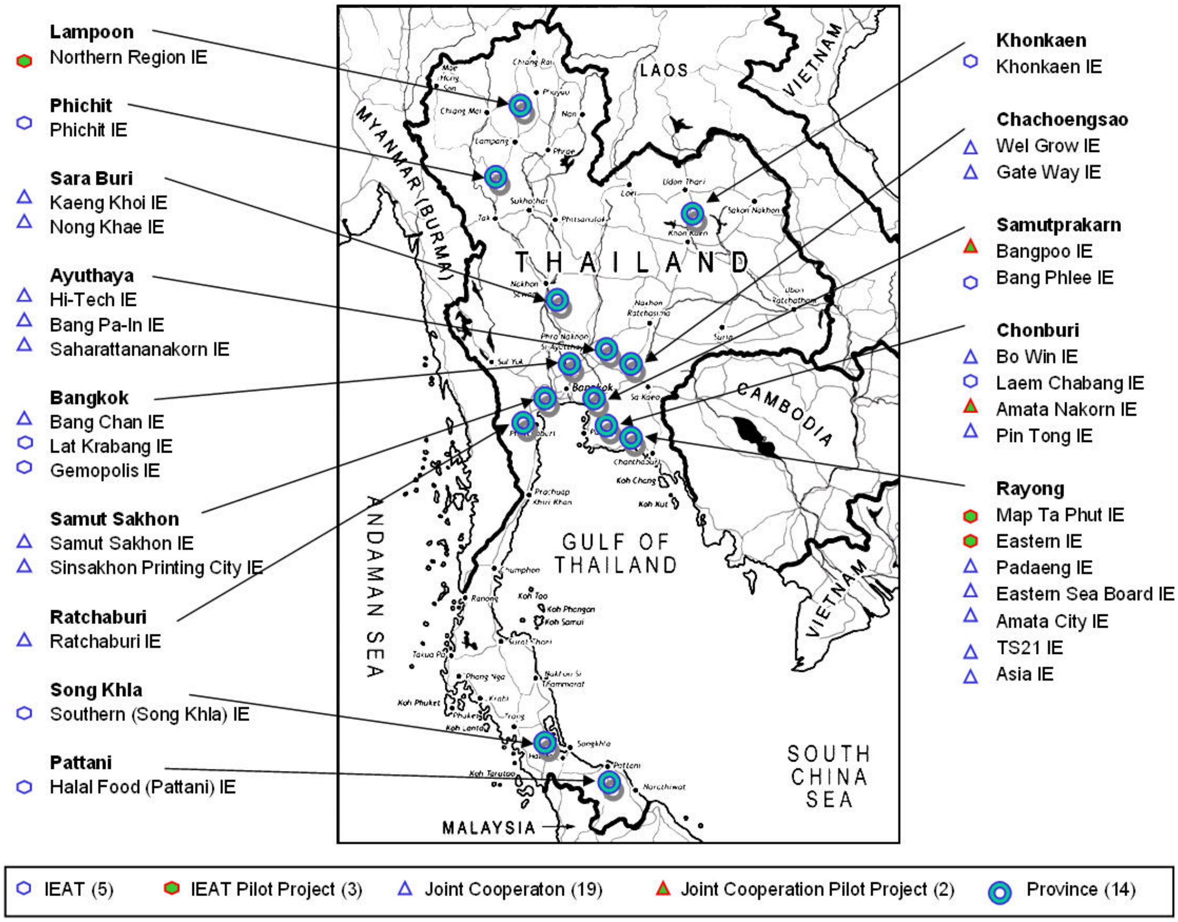


Figure 2-5: Eco-industrial estate and networks in Thailand (source: modified from Wongdeethai, 2005).

Currently, there are 31 Industrial Estates situated in 14 provinces throughout the country, which: 5 IEs are operated by IEAT (displayed with a hexagon symbol in the figure); 3 EIEs Pilot Projects are operated by IEAT (displayed with a highlighted hexagon symbol in the figure); 19 IEs are operated by Joint Cooperation between IEAT & Private Sector (displayed with a triangle symbol in the figure); and 2 EIEs Pilot Projects operated by Joint Cooperation between IEAT & Private Sector (displayed with a highlighted triangle symbol in the figure above).

The five eco-industrial estate and networks pilot projects are: (1) Northern Region Industrial Estate (NR IE); (2) Bangpoo Industrial Estate (BP IE); (3) Amata Nakorn Industrial Estate (AN IE); (4) Map Ta Phut Industrial Estate (MTP IE); and (5) Eastern

Sea Board Industrial Estate (ESB IE). These five pilot projects studies were used to formulate the Thai eco-industrial estate and networks directions, exchange information, in collaboration with other industrial estates and private sectors for better performances and sustainability.

To date Thailand has set up a new high environmental and socio-economic standard approaches to achieve the new target standards involved strengthening cooperation among groups in the eco-industrial estates. Understand the concepts of integration, networking, innovation, waste as resources, and symbiosis, and bringing these into practice by means of the Development of Eco-industrial Estates and Networks (DEE+Net) project. Information of this concept has been disseminated, and encouraged across all industrial estates. Results and feedbacks from the five pilot projects are used for improving plan and to make implementation subsequently. An industrial estate, which has shown good performances can apply to become eco-industrial estate, and eco-industrial network, e.g., MTP IE, and NR IE, respectively. The pilot projects have their cores ‘eco-industrial concept, which is very simple and dynamic and similar to the symbiotic system. Efforts are made to close the loops of production and other activities in order to make suitable and safe destination of all outputs and emissions (Wongdeethai, 2005).

2.3.4 Summary of Industrial Ecology

The main goal of industrial ecology, industrial symbiosis, and industrial metabolism, is to enable sustainable development at local, regional and global levels through sustainable use of resources, preserving ecological and human health by the maintenance of the structure and function of ecosystems. Many examples of these conceptual ideas are developing around the world.

2.4 Product Design

Product design or product development is the process of mapping customer, corporate, and governmental requirements into a product that can be produced and marketed (Ulrich, 1995). Totality of the activities with which all the information necessary for producing and operating a technical system or a product is processed in accordance with the task is called “design process” (VDI 2221, 1987). A product that is shaped by the hands of craftsmen hardly ever required design drawing. In modern industrial production a product design is essential. Almost every designer makes drawings, not only to document the design for the manufacturing process, but also because drawing is a powerful aid when creating a design (Copisarow, 1970). Yet, designing a product is much more than drawing. First and foremost it is a goal-directed thinking process by which problems are analyzed, objectives are defined and adjusted, proposals for solutions are developed and the quality of those solutions is assessed. Product design demands a multidisciplinary approach; which disciplines have to contribute on what extent depends on the characteristics of the product to be developed, but engineering design, industrial design, ergonomics, marketing and innovation management are nearly always involved (Ulrich, 1995).

2.4.1 Product Design Fundamental

The goal of manufacturing is the production of a number of products according to a particular design. This goal is the material goal of the product development process. Often, the starting point before production is to answer the questions, what product is going to be produced and served? what is it propose, function? To answer these questions, the producer should have at least an idea of what the product can do? (product idea). After that the idea has to be polished e.g., by following the idea development process (see **Figure 2-6**).

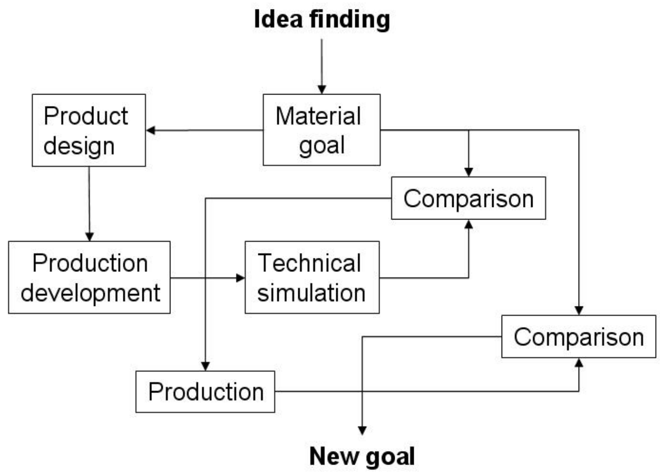


Figure **2-6**: The idea development process (source: modified from Roozenburg, 1995).

Start from top of the figure: (1) the initial idea comes first (material goal); (2) structuring and forming the idea (product design, product development, technical simulation), then (3) compare with alternatives, which finally results in a new (appropriate) goal.

2.4.2 Product Design Method

The core of designing "reasoning from function to form" is especially evident in the creation of a principal solution, for the principle solution marks the transition of the abstract functional structure to the concrete material structure of the product to be developed. Reasoning from function to form does not lead to a unique answer. Any function can therefore be realized by different methods (e.g., design, production), and thus give different solution principles and principle solutions (see **Figure 2-7**).

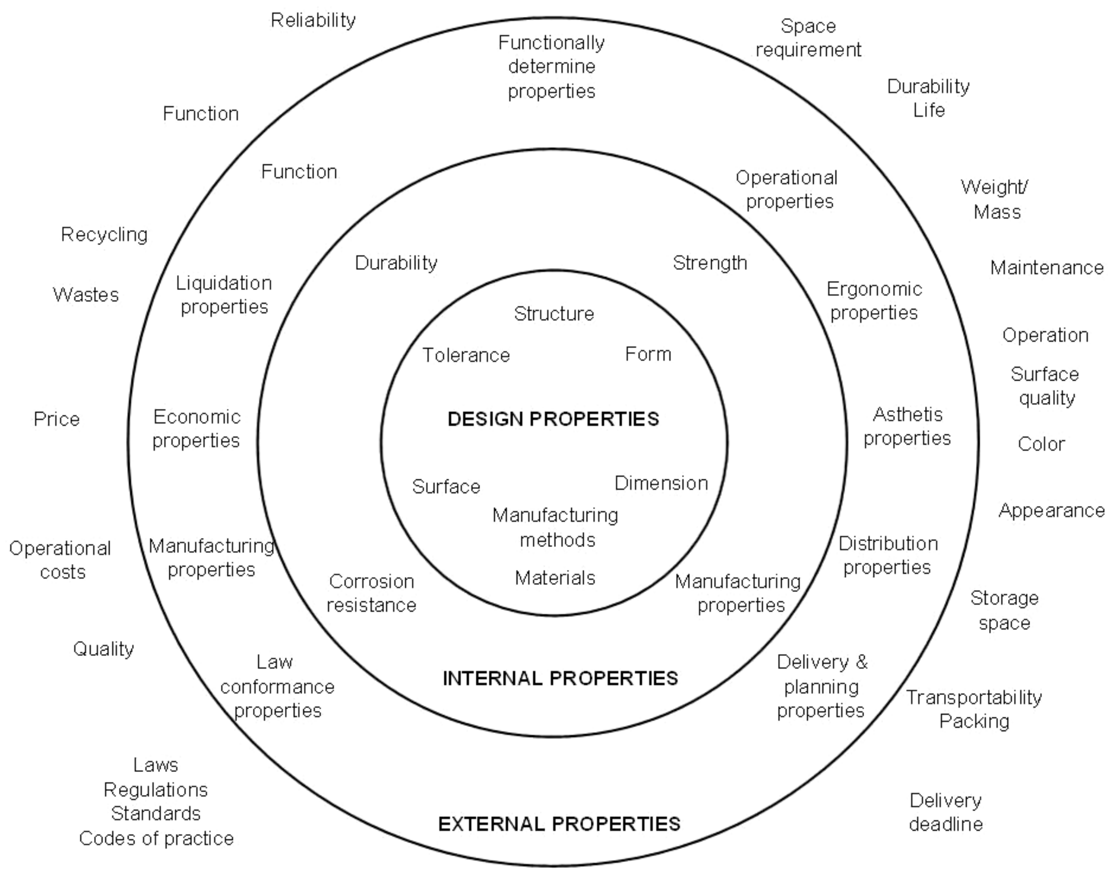


Figure 2-7: Properties of technical system (source: modified from Hubka, 1988).

Hubka & Eder (1988) distinguish external properties and internal properties roughly. This corresponds to "external" and "internal" properties of the product and its environment in relation from one to another. From the figure, "external properties" (e.g., law conformity, manufacturing, economic, liquidation, function, operation, ergonomic, aesthetic, distribution, and delivery & planning) have relationship with "internal properties" (e.g., corrosion resistance, durability, strength, and manufacturing), or vice versa which having "design properties" (e.g., structure, tolerance, form, surface, dimension, material, and manufacturing method) as the structure of the entire product and core considerations.

Form the figure, "External properties" (detail, see outmost items, e.g., law, regulation, standard, codes of practice, quality, operational costs, price, waste, recycling, function, reliability, space requirement, durability life, weight, maintenance, operation, surface quality, colour, appearance, storage space, transportability packing, and delivery deadline), are the influential factors on the product properties which mostly are involved at the designing. Most “design properties,” and “internal properties,” can directly be determined by the designers. In contrast, only some “external properties” that cannot be determined by the designers. A preliminary design is the following and last before the definitive design. A product design is ready for production when all design properties have been specified clearly in the definitive design for all requirements.

2.4.3 Product Development as a Whole

Roozenburg & Eekels (1995) describe a product development as the interaction between the technical and the commercial development processes, a holistic view. All development sub-processes are iterative, the number of iterations that will be needed cannot be said precisely, neither can the iteration after which a sub-process will be influencing another one. The design processes is considered as information processing. The results are transported either back, or to the next sub-processes, or they lead to the decision to stop the project (see **Figure 2-8**).

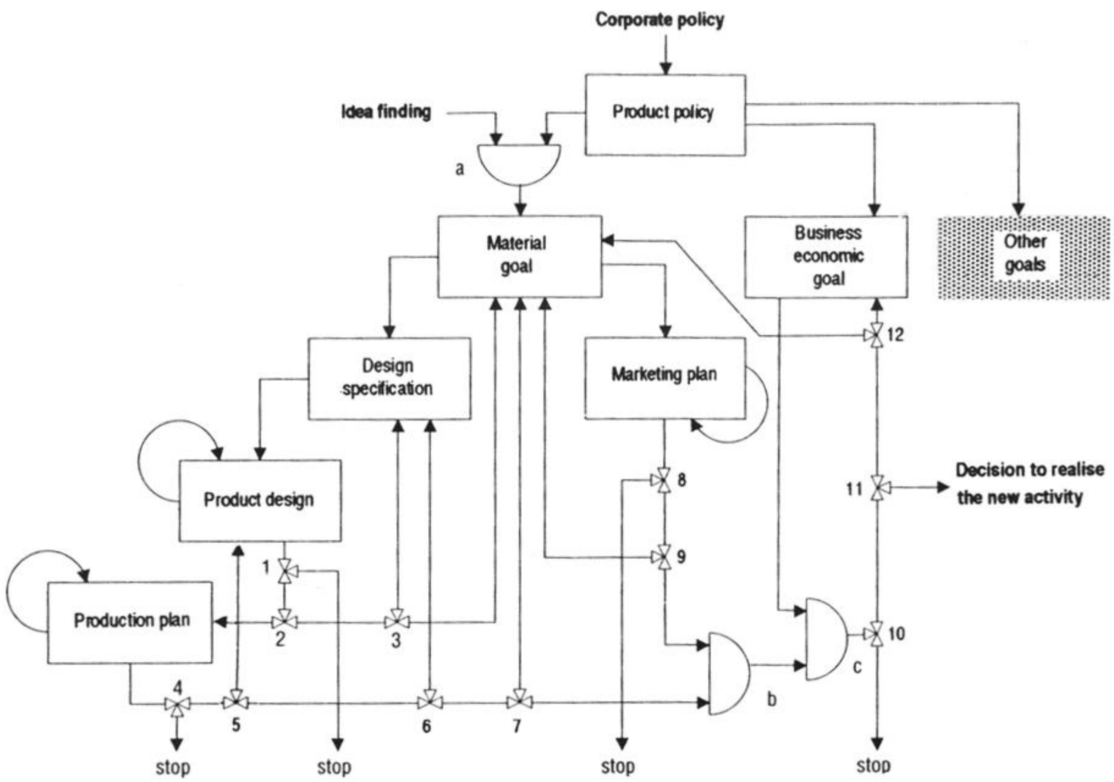


Figure 2-8: Product development as a whole (source: Roozenburg, 1995).

From the figure, at top is the corporate policy, which comprises the product policy. In the latter stage, it is stated which sort of products the company wants to manufacture, and which business economic and higher goals are pursued with these products. "The logic of product development – in product development everything has to do with everything and everything proceeds into everything". Sometimes there is no logic in product development and consequently a methodical approach is meaningless (Roozenburg, 1995).

Indeed, because of the iterative structure of the different sub-processes, its does seem as if the sub-plans for the new business activity can be made in a random order. But this is only seemingly so, because the plans for the product, production and marketing can be in different stages of elaboration. If we take this into account, the product development process, as to be seen as an invariant logical structure, is the basis for effective and efficient product development projects. It is not an organizational scheme. It indicates what has to be done and in what connection, but it does not tell who has to do what (Roozenburg, 1995). By thinking on the whole picture of the product development; there are main points in every discipline's contribution but valuable suggestions and ideas can and should come form other disciplines. The use of this idea ranges from the design of the product to all other plans of the new business activities.

2.4.4 Divergence and Convergence in Design Process (VDI 2222)

After having a rough product idea for designing a new product model, it is necessary to incorporate and formulate other ideas and concepts altogether. Roozenburg & Eekels (1995) describes the use of pattern of divergence and convergence for considering the product model, a so-called "phase model." A process that has sub-processes within, should stretch out all possibilities to see and determine alternatives clearly, as described in Design Engineering Methodics – Conceptioning of Industrial Products (see **Figure 2-9**) (VDI 2222, 1977).

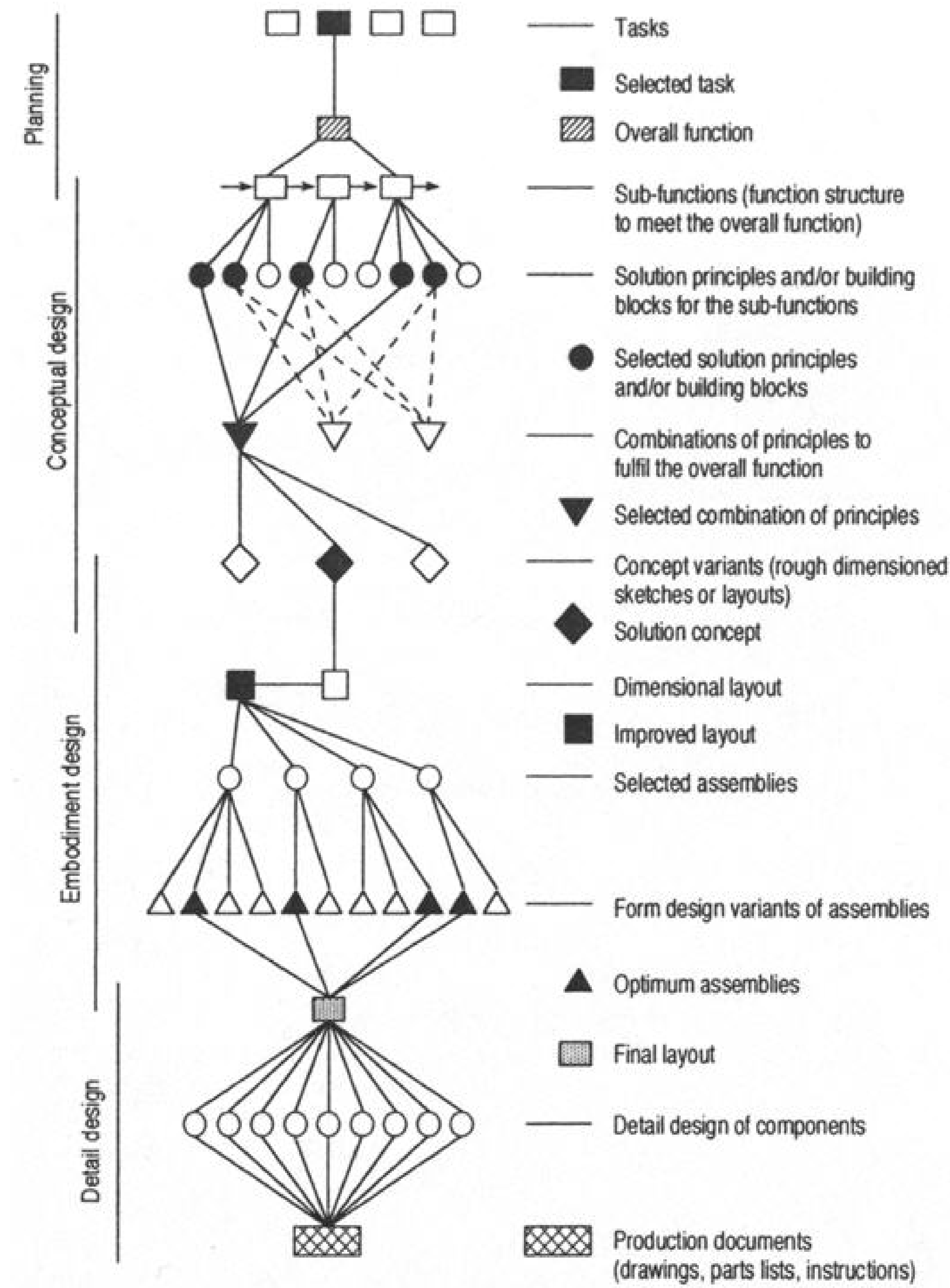


Figure **2-9**: Divergence and Convergence in the Design Process VDI 2222 (1997). The shadowed elements indicate the chosen points of departure for the next phase.

From the figure, the expansion of process “divergence” in the design phase is the determination process of some other available alternatives, e.g., in product sub-functions; function structure to meet the overall function; solution principles and/or building blocks for the sub-functions; concept variants (rough dimensioned sketches or layouts); selected assemblies; from design variants of assemblies; and detail design of components. Sub-processes, which can be merged into one process should be collapsed down to facilitate finding the most appropriate choice, see the figure. The contraction of sub-processes “convergence” in the design phase is the determination process for selecting the task (highlighted in the figure) e.g., combinations of principles to fulfil the overall function; solution concept; improved layout; final layout; and product documents (drawings, parts lists, instructions).

2.4.5 Summary of Product Design

Empirical research into the design process is somewhat relevant to several research areas whereas they are mostly developing their own approaches, options on the value of the product design as a heuristic tool for designers are mainly based on individual experiences and belief in its rationality.

2.5 Design for X (DFX)

Design for X, X stands for multi-objective satisfaction e.g., Design for (Manufacture, Assembly, Environment, Recycling, Reliability, Service, etc.) It is important to keep a broad perspective on the related research areas, as a result, the links of diverse information from different disciplines can be investigated and elaborated, and thus following sections are dedicated for the DFX.

2.5.1 Design for Manufacture and Assembly (DFM/A)

DFM/A fundamentally considers on the basis goals of increasing the feasibility of manufacturing and assembling system and lowering the production cost. Manufacturing system is a system created to manufacture certain products or to carry out phases of product manufacturing (Määttä, 2004). The same pathway as manufacture and assembly process but considered in up-side-down direction, is the disassembly process. “Design for (ease of) disassembly,” DFD, or “reversed manufacturing,” is the study of how to manufacture products in such a way that ease disassembly. In product design for manufacture, assembly, and disassembly, joint types and product structure play a very important role and thus influence the product disassembly efficiency.

Design for disassembly allows the assessment of products at their end-of-life virtually. Consideration of design criteria and proposed design alternatives provide a great deal of product improvement at the design stage. Information and networking among producers, users, and recyclers are formed up to provide and receive information for further use by other users and researchers (Seliger, 1995). High performance productive disassembly factories are needed to deal with the increasing streams of used household products.

2.5.1.1 DFA Methodology

In 1970s, several books and publications from G. Boothroyd described and promoted the use of DFA method in industry (Chan, 2003). The aim of *design for assembly* (DFA) is to simplify the product structure to reduce the assembly cost. Consequently, it usually improve product quality and reliability, as well as a reduce manufacturing equipment and part inventory. These dual benefits often outweigh the reduction of the assembly cost, the “Boothroyd-Dewhurst Method” is one of the well know design methodology which is based on two principles: (1) the application of criteria to each part to determine if it should be separate from all other parts; (2) estimation of the handling and assembly costs for each part using the appropriate assembly process. The following example describes the product model before and after application of DFA method (see **Figure 2-10**).

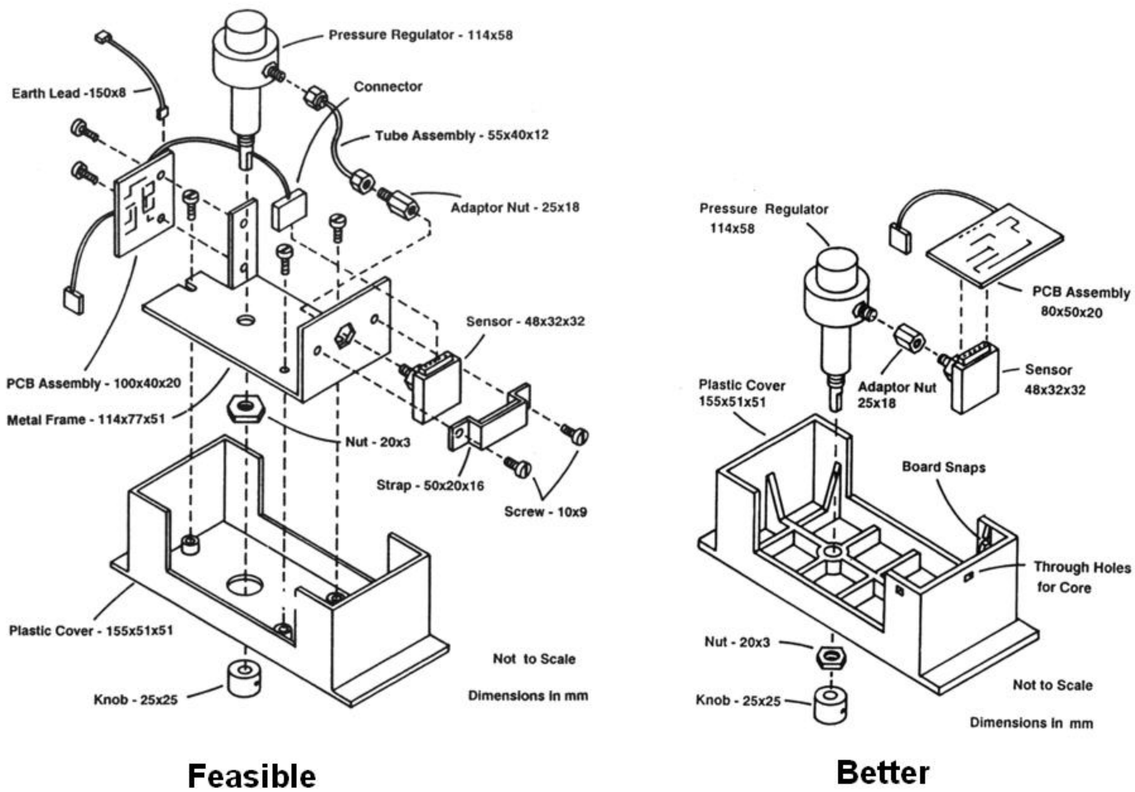


Figure 2-10: Conceptual re-design of switch controller assembly (source: Boothroyd, 1994).

The list of all parts is then evaluated to obtain the minimum number of theoretically needed parts. This method relies on an existing design which is iteratively evaluated and improved by the four process steps. These process steps are: (1) Select an assembly method for each part; (2) Analyse the parts for the given assembly methods; (3) Refine the design in response to shortcomings identified by the analysis; and (4) Loop to step-2 until the analysis yields a sufficient design (Boothroyd, 1989). This analysis is generally performed using tables to estimate the part *handling* and part *insertion* time. Moreover, parts are evaluated as to whether it is really necessary in the assembly, by asking three key questions: (1) Does the part move relative to another part? (2) Are the material properties of the part necessary? and (3) Does the part need to be a separate entity for the sake of assembly? (Boothroyd, 1989). By going through the four process steps and finding answers to the three key questions (and if necessary the iteration can be made until the results are optimal and satisfy), in general the method can improve several design elements of the product.

2.5.2 Design for Recycling (DFR)

Proposed "take-back" policies in Europe, recycle-oriented product development, eco-label requirements, and increased environmental awareness have motivated industry on improving their products recyclability and enhancing their products design.

Design for recycling considers the methods to improve recycling of raw materials or components by facilitating assembly and disassembly, ensuring that materials are not mixed through appropriate labeling of materials and components (Natural Step, 2003). It has become an essential feature of environmental management tool for product manufacturers in recent years. The integration of harmful materials (if really necessary) has to be carried out in a way that provides separation by simple means. Thereby the remaining can be reprocessed much easier (Meerkamm, 1995).

This study focuses on DFR. Relevant and extended issues, and their applications have been reviewed and described in the following sections, which include the subjects of: (1) Prioritization of design for recycling; (2) Automotive recycling; (3) Recycling targets for end-of-life vehicle – ELV Directive (2000); (4) Design of technical system and products VDI 2221 (1987); (5) Recycling-oriented product development VDI 2243 (2000); (6) Guidelines on recycling-optimized product development; and (7) Design recommendation.

2.5.2.1 Prioritization of Design for Recycling

W. Masanet (2002) carried out a research on the comparison between the guideline from the Swedish Confederation of Professional Employees (TCO), "TCO 99" (Swedish's eco-label) and the guideline from the German Regulatory Association (RAL), "Blue Angle" (German's eco-label), on design for recycling guidelines. Design for recycling guidelines for computers (Boswell, 2000) together with industry guidebooks (APC, 1998) have been used to compare the two eco-label criteria. In common, different DFR guidelines aimed at improving the recyclability of products on different concerned magnitudes. These variations depend largely on the source of origins, and specific regulations on different countries. Results from this research, point out that the design for recycling guideline for plastic components from the two eco-label schemes are not always effective for improving the recyclability of plastic components (see **Table 2-1**).

Table 2-1: DFR Guideline (source: modified from Masanet, 2002).

No.	Design for Recycling Guideline	TCO'99	Blue Angel
1	Plastic component > 25 g labeled per ISO 11469	R	R
2	Large plastic parts limited to one polymer type	R	
3	Large plastic parts must not be painted such that weight is increased by more than 1%	R	
4	No molded-in or glued-on metal parts	R	
5	All plastic parts of same polymer type shall be same color		S
6	Use of Snap fasteners wherever possible		S

R = Required for eco-label certification, S = Suggested

Evidently, from the table the row number 2, 3, 4, 5, and 6 have illustrated that the design for recycling guideline are not always necessary for both eco-label schemes. In summary, the design for recycling guideline is the criteria that describe necessary possibilities, which can potentially improve the recyclability of products. It can be seen that it is not a must for every point of the criteria to be applied. Further results show that some criteria are effective for manual systems but may not be appropriate when apply to automated system e.g., use of ISO labels (see **Table 2-2**).

Table 2-2: Prioritization of DFR Guideline (source: modified from Masanet, 2002).

No.	DFR Guideline	Effectiveness for:		Design Priority
		Manual Systems	Automated Systems	
1	Use of ISO labels	High	None	High
2	Use of one polymer for all large parts	Low	Low	Low
3	Limting the use of paints	High	High	High
4	No molded-in or glued-on metal parts	High*	Low	High
5	Use of one color for each polymer type	Low	Low	Low

*for molded-in metal parts only

The outcome of the research design for recycling guideline prioritization can be used to help prioritize design for recycling strategies, which can optimize both product recyclability and design productivity.

2.5.2.2 Automotive Recycling

There are a number of unique activities, which take place in the automotive recycling processes. Some automotive recycling facilities, have one recycling process involved, while in others, multiple activities are taking place. Several players are involved at different stages of automotive life-cycle from products manufacturing until their end-of-life. The aims of all players are to optimize the net profit and the sustainability of product/process through out all activities life-cycle. This means that all involving unit processes have to be taken into consideration. The recycling units processes usually include (1) manufacture, (2) utilization and maintenance, (3) dismantling (fluid draining, parts removal, powertrain removal) (US EPA, 2001), (4) recycling, (5) shredding, and (6) end-of-life treatment.

The automotive dismantling processes, involve handling a significant quantity of hazardous materials. In most case, the complete disassembly of vehicles are carried out (Environment Canada, 1996). Some recyclable/valuable parts are cleaned and stored for resale. Tires are either resold, or sent to a tire recycler. The remaining parts (cores) may be sold to scrap metal recyclers, core suppliers, parts rebuilders, or crushed with the vehicle body and sold to steel recyclers. J.C. Alonso (2004) has elaborated checklists for optimization of the automotive recyclability, economics, and environmental aspects. The practitioner needs to figure out and answer the following questions:

1. How to reduce the dismantling time (and cost)?
2. How much is the optimum dismantling percentage?
3. How to solve the logistic problem?
4. How to improve the separation of the different plastic fractions?
5. Is it possible to find a market for the separated plastic fractions?
6. How to improve the metal recycling processes to obtain purer fraction (e.g. copper, precious, metals, etc.)?
7. What is the optimum end-of-life scenario considering environmental and economic aspects?
8. Is it possible to use intelligent materials to improve the dismantling process?

These checklists help to formulate idea for developing the recycling system and the design guidelines for automotive. Improving these key factors can enhance the automotive recycling system. Several studies have to be done, in order to achieve an optimization of economy, societal, and environmental performance. The development of design guidelines, use of innovative material, prototyping, testing of illustrative samples, and development of methodologies & software tools help to support recyclers and designers' decisions.

2.5.2.3 Recycling Targets for End-of-Life Vehicle (ELV Directive)

A tightening legal situation and exploding cost for landfills require the recycling of used products in addition to ecological reasons. In order to reduce material consumptions and loop-closing for automotive manufacturing, the EU Directive 2000/53/EC (2000) end-of-life vehicle (ELV), has set the recycling targets (% by an average weight per vehicle and year), which can be summarized as (see **Figure 2-11**):

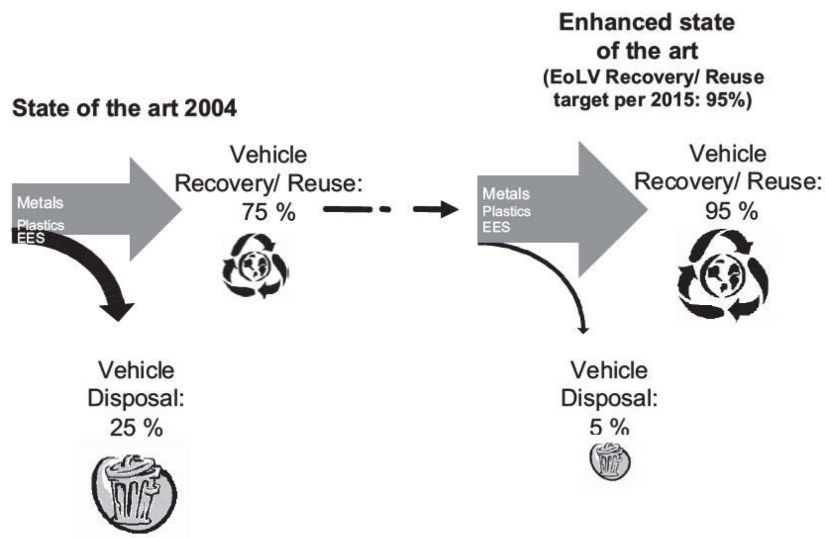


Figure 2-11: ELV Directive targets (source: Alonso, 2004).

1. At least 80% (by an average weight per vehicle and year) of EOL car should be "reusable and recyclable", and 85% of EOL car should be "reusable and recoverable," by 1 January 2006.
2. At least 85% (by an average weight per vehicle and year) of EOL car should be "reusable and recyclable", and 95% of EOL car should be "reusable and recoverable," by 1 January 2015.

The disassembly of worn-out products allows recovering of components and subassemblies in product cycles as well as eases recycling processes like material reprocessing. Material such as metal, glass, plastics, resins, electronic equipments presents in cars have to be reduced their separate components to increase their recyclability.

From the figure, in 2004, the current average reuse and recycling rate for vehicles is about 75% (Alonso, 2004). It is evident that more components, parts and materials from ELV could be achieved when design guidelines for recycle, and other tools are applied in addition to research and development to achieve the target of nearly 100% recycling in the year 2015.

2.5.2.4 Design of Technical Systems and Products (VDI 2221)

To make a recycling-oriented product/system development; it is necessary to understand keys effective factors before the technical requirements can be drawn. In VDI 2221 guideline (1987), the proposals for a systematic approach to designing technical systems and products are given (see **Figure 2-12**). This guideline aims to construct the approach for design, which is applicable to a wide variety of tasks, and transcends specific branches of industry.

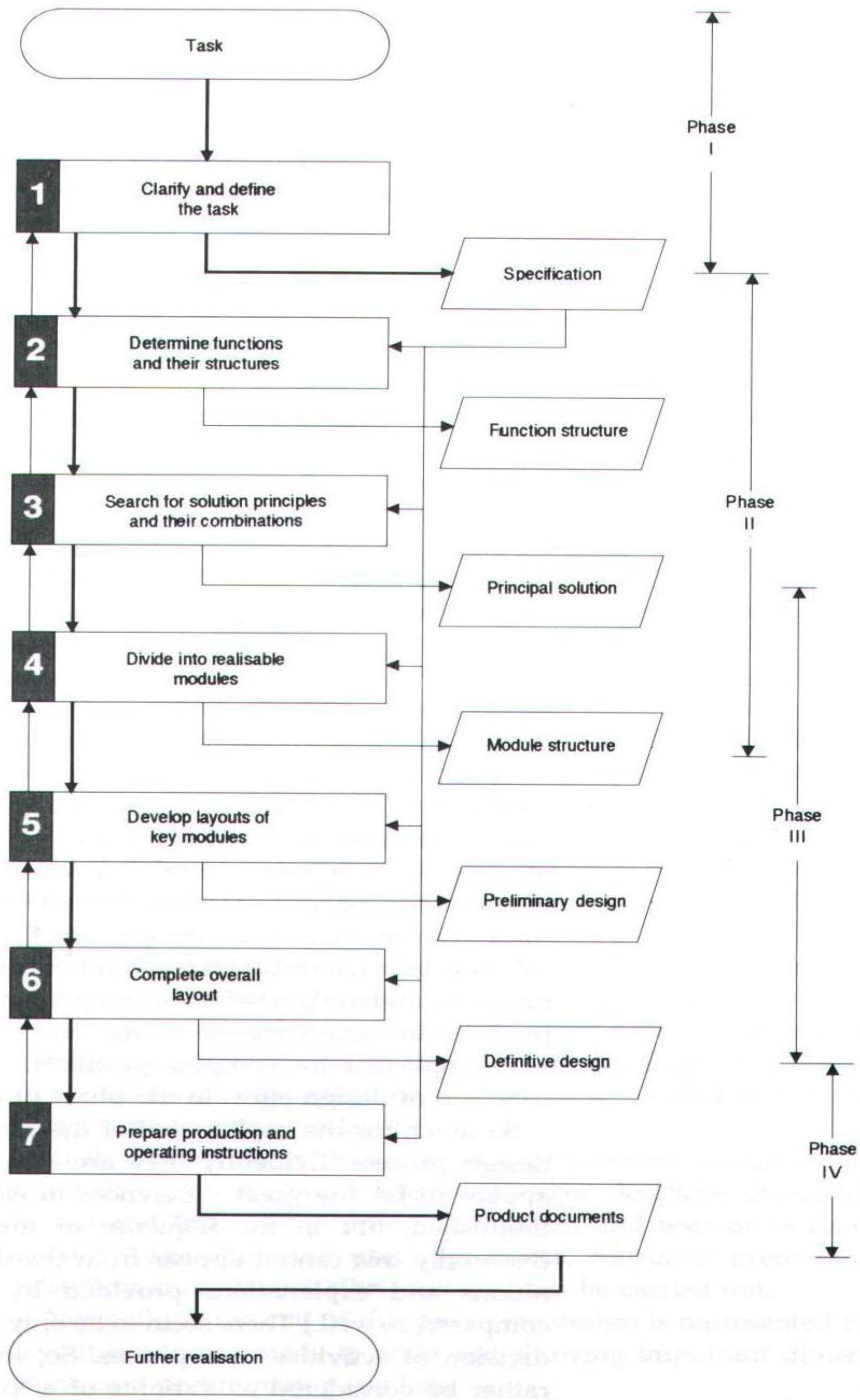


Figure 2-12: Systematic approach to design according to VDI 2221 (1987).

A Systematic Approach to the Design of Technical System and Products is explained in the figure (VDI 2221, 1987). Above all the objective must be defined i.e., Task. After that the Task must be pursued in the following steps: (1) Clarify and define the Task (on the specification); (2) Determine functions and their structures (function structure); (3) Search for solution principles and their combinations (principle solution); (4) Divide into realizable modules (module structure); (5) Develop layouts of key modules (preliminary design); (6) Complete overall layout (definitive design); and (7) Prepare production and operating instructions. The idea is to integrate of recycling-orientation of product/system during these design steps/phases. In each step when the idea/goal is not satisfy then the previous step(s) can be reconsidered and resolved until satisfied. The final goal is to produce the product documentations. If appropriate or when necessary a further realization (a higher target goal) can be introduced, and considered as a new Task.

2.5.2.5 Recycling-Oriented Product Development (VDI 2243)

VDI 2243 guideline (1993), German recycling standardization, provides engineers a quick and relatively complete overview of useful issues to be considered in modern design for recycling. The 35 page long VDI 2243 guideline includes the issues of material and waste recycling: waste streams in production; product recycling (during a product's useful life): goals, processes involved; and rules for the designer. The product design guideline for recycling-optimized product development and design recommendation are described in the following sections.

2.5.2.6 Guidelines on Recycling-Optimized Product Development

A rough checklist in VDI 2243 recycling-oriented product development (2002), a simple tabulated guidelines and quick assessment (qualitative assessment), is displayed in **Table 2-3**.

Table 2-3: Rough checklist for recycling-optimized product development (source: modified from VDI 2243, 2002).

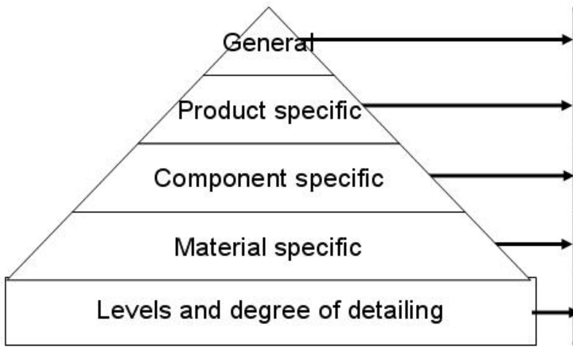
No.	Technical Recycling Criteria	Assessment	Potential Optimization by
1	**Suitability for materials recycling**	recyclable, identical properties	no optimization necessary
		recyclable, inferior properties	test use of higher-grade materials
		not recyclable, disposal necessary	use recyclable materials
2	**Recycling compatibility**	compatible, identical properties	no optimization necessary
		compatible, inferior properties	possibly optimized material variety
		incompatible	use compatible materials
3	**Identifiability**	clear, simple, machine-readable	no optimization necessary
		readily separable, no marking	at least provide marking
		impossible, no marking	avoid, provide marking
4	**Recycling-critical materials**	not present	no optimization necessary
		present, marked, readily separable	at least provide marking
		present, inseparable, disposal necessary	avoid, provide marking and disassembly
5	**Pollutants and hazardous substances**	not present	no optimization necessary
		present, marked, readily separable	ensure long-term good legibility
		present, inseparable, disposal necessary	avoid, provide marking and disassembly
6	**Recognizability**	clear, visible	no optimization necessary
		not visible, but indication	provide marking
		not visible, not indication	provide indication and marking
7	**Accessibility**	directly accessible	no optimization necessary
		indirectly accessible	possible improve extent of disassembly
		inaccessible	test change to axial accessibility
8	**Types of connection**	detachable nondestructively	no optimization necessary
		partially destructive, only connection	use nondestructive connection
		destructive, including component damage	use detachable connections
9	**Variety of connections**	single/few, uniform type	no optimization necessary
		functionally-specific variety, standardized	test possible reduction
		unmanageably many	reduce the number
10	**Disassembly time**	low	no optimization necessary
		considerable time consumption	test possible reduction
		very high, unacceptable	improve accessibility, use modular construction
11	**Recycling process**	optimum process used	no optimization necessary
		complex process steps required	test compatibilities

In accordance with various technical recycling-related criteria across a range of designs, materials, products and processes, the rough checklist can be used for optimizing the product development with rough recommendations. The Technical Recycling Criteria {first column in the table} describes the technical recycling-oriented concerned issues e.g., (1) Suitability for materials recycling; (2) Recycling compatibility; (3) Identifiability; (4) Recycling-critical materials; (5) Pollutants and hazardous substances;(6) Recognizability; (7) Accessibility; (8) Types of connection; (9) Variety of connection; (10) Disassembly time; and (11) Recycling process. The Assessment {the second column in the table} describes the rough assessment outcome e.g., status of the investigated product: visible, non-visible, low, high, acceptable, and not acceptable. The Potential Optimization by {the third column in the table} proposes for potential optimization processes e.g., (1) No optimization necessary, (2) Recommend for at least doing something, and (3) Recommend for re-design. The utilization of the quick checklist for recycling-optimized product development (VDI 2243, 2002) could be used in addition to the company internal checklists, and other relevant legislations that are enforced on the product study.

Often, some products can be regulated by more than one regulation such as a compact entertainment system (DVD player + TFT monitor). The same product can be used by different customers, e.g., household customers, and automotive manufacturers (consider as customers). They can be regulated under WEEE Directive (EU Directive 2002/96/EC), which regulates electronic products, IT products, e.g., entertainment equipment (see **Appendix B-1**), and/or ELV Directive (regulate end-of-life vehicle, e.g., when entertainment systems are preinstalled in cars from manufacturers). Therefore, when considering these kinds of products attention should be given to a variety of legislations.

2.5.2.7 Design Recommendation

The VDI 2243 (2002), has identified and classified the recycling-oriented product development on the issue of design recommendation into five key issues e.g., (1) general issue (recycling concept, detachability, and recyclability); (2) product issue (modular construction, type and range of connections, and compatibility for use); (3) component issue (accessibility, dismantling level/time, and multiplicity of materials); (4) material issue (separability, dismantling time, and material selection compatibility); and (5) levels and degree of detailing issue (overall structure, connections, and materials), which have been illustrated in a pyramid-like shape, the depth of detail considerations are varied and classified from concept (top) to details (base) (see **Figure 2-13**).



Recycling concept	Detachability	Recyclability
Moudlar construction	Type and range of connections	Compatibility for use
Accessibility	Dismantling level, time	Multiplicity of materials
Separability	Dismantling time	Material selection compatibility
Overall structure	Connections	Materials

Figure 2-13: Design recommendation (source: modified from VDI 2243, 2002).

This rough checklist guides the users on what criteria have to be taken into consideration at which stage. Because of the fact that, most products have a longer period of time between the product development and the recycling process; during this period the recycling technologies can be changed and then the product structures are no longer optimal for these technologies. Therefore, while designing and underlining the product functions and product details at the design stage, the designer's visions, especially on trends of product development are necessary.

2.5.3 Design for Environment (DFE)

A green design or design for environment is an optimization process with the goal to minimize the detrimental impact of the product on the environment throughout its life-cycle. "The absolute "green" product, i.e., a product that has no negative impact on the environment, does not exist" (Schott, 1995). The demands on green products, however, have to be satisfied by production, reduction of the detrimental effects on the environment as much as possible. A number of manufacturers uses DFE concept to increase their products performances while protecting the environment by making a better design. One of the most important features of DFE is that it optimizes types of connection within the product. Ingenious fasteners are preferred, which give the product unique and increase the overall product performances. Fasteners are not only critical to optimizing product functions, but also to the ultimate disposal and recycling of that product. The well design fasteners are easily detached for quick disassembly to allow products to be upgraded, or repaired with ease or recycled at their end of life (Cook, 2001).

2.5.3.1 Design for Environment Strategies

Industrial research assistance program (IRAP-PARI), Canada, which provides innovative assistant towards DFE to numerous firms, has developed and classified DFE strategies into seven different streams:

1. *New concept development*. To examine and improve the product functions assumptions (dematerialization; increase shared use; and provide a service).
2. *Physical optimization*. To simplify the product design with regard to its functions (integrate product functions; optimize functions; increase reliability and durability; easy maintenance and repair; modular product structure; and strong user-product relationship).
3. *Optimize material use*. To use environmentally sound materials, surface treatments (cleaner materials; renewable materials; lower energy-content materials; recycled materials; recyclable materials; and reduce material usage).
4. *Optimize production*. To implement cleaner products and processes (increase efficiency; prevent pollution to air, water and land; and minimize risk to human health and the environment: alternative production technique; fewer production steps; lower/cleaner energy consumption; less production waste; and fewer/ cleaner production consumables).
5. *Optimize distribution*. To increase transportation efficiency (less/cleaner/re-usable packaging; energy-efficient transportation; and energy-efficient logistics).

6. *Reduce impact during use*. To increase product efficiency (lower energy consumption; cleaner energy sources; reduce use of consumables; cleaner consumables and auxiliary products; reduce energy and other consumable waste).
7. *Optimize end-of-life systems*. To minimize product's EOL impacts (product re-use; design for disassembly; product re-manufacturing; material recycling; cleaner waste treatment).

Each year, these criteria are being used to assist 12,000 SMEs within the support umbrella of the National Research Council-Industrial Research Assistance Program (NRC-IRAP), the Canada's premier innovation assistance program for small and medium-sized enterprises (SMEs) (IRAP-PARI, 2005). Example of the success stories of companies employing DFE are: (1) IBM Sweden with the artist/designer, Torstensson, J., has designed glassware made from recycled cathode ray tubes (CRTs) by using DFE concept. The face of the CRT comprises two thirds of the weight of the glass and does not contain harmful lead. It results cost-savings in recycled materials (Belmane, 1999); (2) Henkel use DFE as a new business strategy on providing services rather than products, e.g., offering surface treatment and degreasing services to its automotive clients, which lead to improved products, long-term contracts and supplier security. Service-based sales have increased by up to 200 per cent in the first year (Rowledge, 1999).

2.5.3.2 Approaches of Design for Environment

In the past few years numerous approaches to support DFE have been developed. Unlike the DFR approach which is found to be the ubiquitous dissemination concept that focus specifically on just the recycling-oriented design; DFE has more aspects with considerable importance on different magnitudes. Several approaches for achieving DFE objectives have been identified by Schott & Birkhofer (1995), as follows:

1. *Recycling approach*. Reducing consumption of raw materials.
2. *Hazardous waste approach*. Reduction of hazardous waste.
3. *Energy indicators approach*. Minimization of energy consumption.

4. *Life-cycle assessment approach*. Recording detrimental impact on the environment.
5. *Eco-quality approach*. Increasing the quality of the environment.
6. *Environmental economic approach*. Setting off environmental damage.
7. *Environmental marketing approach*. Increasing eco-marketing.
8. *Environmental legislation approach*. Changing legislation.
9. *Eco-audit approach*. Realization of environmental management systems.

When carry out study on these approaches, some problems occasionally come to the surface, e.g., (1) inaccurate evaluation of consequence of a design solution, (2) vast quantity of data has to be collected and formulated by designer(s). These problems occur because of specific constraints and limitations; this will be discussed in the next section.

2.5.3.3 Constraints of Design for Environment

While making a green design or design for environment, unavoidably limitations and constraints are often involved. Schott, H. (1995) has classified constraints of DFE into four main streams:

1. *Constraints caused by the own company*. The engineering design department is not only responsible for ecological criteria, but also for the technical functions, economic feasibility and quality of their designs.
2. *Constraints due to the decrease of net added value by the company*. The increasing amount of outsourcing leads to a decrease of available options for a company to reduce negative environmental effects.
3. *Constraints due to normative condition*. The multitude of legal and technical standard and specifications complicate the creation of useful design guidelines for the designers.
4. *Constraints due to the extent of data to be collected for life-cycle-assessment*. In order to make the environmental impact assessment of a technical product over the product-life-cycle a vast number of data has to be collected.

A crucial restriction encapsulates the constraints of own company are (1) the decrease of net value by the company; (2) normative conditions; and (3) the extent of data to be collected for life cycle assessment, and (4) a time-to-market control which obviously is the dynamic driving force behind product design. Because of these specific constraints, design engineers are often forced to use a poorer solution, which does not fully achieve its environmental goals. Candidate designs are sometimes so constrained that addressing environmental goals turns out to be impossible (Sun, 2003). The decision for DFE is made during the process of optimization with the goal to maximize the overall product performance within the constraints.

2.5.4 Summary of Design for X

DFX, where X represents the aforementioned areas or beyond, has shown different methodologies and concepts that are employed however, their fundamental aspects are in line with the recycling-oriented product design. “Concurrent Design” is another discipline closed to DFX, both have potential expandable for new fields of applications. The concept of concurrent design process or “overlapped product development” (Roemer, 2000) is not limited to one issue, rather is extends under goals cascading across various aspects toward total compromise of overall design requirements (Koopman, 1999). By putting all different engineers in one room for brain storming the cross-functional ideas of a new approach could be found. Pattern of concurrent design process formulation is flexible regarding the objectives of the merging disciplines and thus more powerful, than using single methodology/approach/concept to solve problem with multiple constraints, that are relevant to other areas.

“Continuous improvements in performance accompanied by continuous increase in complexity and cost,” are no longer the right paradigm in the 21 century, rather “technologically superior products and services at affordable cost” (Raj, 1998). For instance, concurrent design can be used to resolve the aspect of costs & benefits analysis e.g., what is the minimum unit to be produced to start obtaining the benefit (the break-even point), regardless the issues of product efficiency, environment and others? Two main constraints/options for this question are given as: (1) manufacture modeling e.g., warehouse, specific machinery – {fixed cost}; and (2) product modeling e.g., labor, material, energy – {production cost and sell benefit}. Furthermore, the concurrent design facilitates design consideration across various aspects, e.g., (i) different disciplinaries; and (ii) life-cycle phases, by using geometric modeling and consequent integration with engineering analysis, but the sum of them cannot perform design itself due to the lack of synthesis viewpoint (Fujita, 2005).

Several efforts for elaborating and merging concerned aspects/disciplines into one approach are getting more attention, many of them have the efficiency drawbacks, but some have positive results e.g., (1) GaBi 4.0 software package with SoFi and DFX, boast that it could share database for handling on LCA, LCE, MFA, SM, and DFX/R (PE Consulting Group, 2005); and (2) euroMat software can be used for various DFE applications including LCA, LCC, risks, manufacturing, recycling (euroMat, 2004). The use of the computer for executing commands on complex databank, helps solve sophisticated problems and is being employed for more and more applications. Obviously, a new multi-purposal assessment tool, which has abilities to evaluate the merged concern aspects, will be based on computer-supported concurrent engineering (Fujita, 2005).

2.6 Eco-design

In 1990s Eco-design became a major topic when environmental-related strategies shifted from end-of-pipe to integrated measures. The eco-design aims to reduce the environmental load of product from cradle to grave perspective. The scientific principle behind this practice is the life-cycle thinking. Nowadays eco-design is applied frequently in several manufacturing sectors, but mostly as an "add on" activity or a separate case study, it rarely uses as major product design (Pascual, 2004). However, the tendency for the use of eco-design is bright because it brings benefits to the company when applied appropriately, e.g., (1) reduce the product/production costs, and (2) reduce environmental treatment costs.

2.6.1 Eco-design Guideline

The need for eco-design guideline as a tool guiding producers for the development of green products is evident, especially, for SMEs that do not have capacity for basic research. Eco-design guidelines are together with LCA and IPP tool; in product design, integration of environmental considerations at the design stage is an efficient way to reduce the environmental impact though out the entire life of the product. For instance, Eco-design guideline developed by the Centre for Sustainable Design, University College, UK (Charter, 2002) uses for general electronic & electrical suppliers, and SMEs (see **Table 2-4**).

The environmental potential of developing guidelines for product groups with high environmental impact (electronics) is clearly visible. The potential of coordinating the existing guidelines and making them generally available are likely to be achieved.

Table 2-4: Eco-design guideline for SMEs (source: Charter, 2002).

ATTRIBUTES	Scrap	Recycle	Resale	Upgrade	Remanufacture
1. Design for second market Must work with range of voltages and operating conditions.			x	x	
2. Durable, high value sub-assemblies Design assemblies containing precious metals, high tolerance components or ICs for reuse. Standardisation helps.		x		x	x
5. Easy access to replaceable parts Design sub-assemblies so they can be dismantled easily without specialist tools. Minimise number of operations to replace these parts; serviceable parts easily accessible.			x	x	x
6. Easy separation of contaminated materials Confine contaminated or hazardous material to a section of the product so easy to identify and remove; avoid such material where possible.	x	x			x
7. Easy disassembly to constituent parts Reduce parts count, variations in size, type and head of fixing screws; use self-threading screws rather than bolts and inserts, alternative fixing types (e.g. snap fits, clips, slots); avoid need for special tools for assembly; make it quick to dismantle.	x	x			x
10. Avoid use of glue and fixing tape Unless destined for disposal, as difficult to remove and contaminate material.		x		x	x
12. Design key pad for disassembly The button array should be easy to remove but remain intact. Silicone button pads should be combined into a single assembly.		x			x
15. Materials identified and marked Mark all materials using internationally recognised codes, especially polymers and other recyclable materials; identify hazardous and other toxic materials; avoid method which will impair reuse or recycling.	x	x	x	x	x
16. Maximise density Ensure no wasted space on the circuit board; put assemblies and loose components in a housing.	x				
20. Minimise material mixtures Avoid laminated or compounded materials as difficult to recycle; where possible use materials of a single type or blend.	x	x			
25. Use recycled materials where possible Adapt designs to encourage use.	x	x	x	x	x

The guideline particularly focus on issues of (1) design for second market; (2) durable, high value sub-assemblies; (3) easy assess to replaceable parts; (4) easy separation of contaminated materials; (5) easy disassembly to constituent parts; (6) avoid use of glue and fixing tape; (7) design key pad for disassembly; (8) materials identified and marked; (9) maximize density; (10) minimize material mixtures; and (11) use recycled material where possible, to highlight their importance on different aspects such as: scrap, recycle, resale, upgrade, and remanufacture (Charter, 2002). The issues of eco-design have been identified on the relevant aspects that need attention or actions.

2.6.2 Eco-design (EuP Directive)

Eco-design requirements for energy using products (EuP) (Directive 2005/32/EC, 2005), requires companies producing energy-using products to take eco-design and environmental awareness into account. The impact of this regulation has twofold, positive and drawback (Stevels, 2004):

1. Positive items – obligation to make an environmental analysis of the product; addressing the complete life-cycle; harmonizing on environmental, economic, technical, functional and other aspects; encourage innovative technology for functionality realization
2. Drawbacks – emphasis on just eco-design could weaken focus on other conditions to become champion (integrated eco-design, wise management); pricey and complicated manufacturer requirements, e.g. documentation of design choices or under the management system for assessing conformity.

The directive focuses on the eco-design applications, as the coin has two sides, the consumers get benefits while the EuP producers undergo reorganization, however, there is the point where both sides are satisfied when the producers produce good quality products and consumers are happy to buy. Global players will need to adjust their systems for EuP, as they experience the impacts of WEEE and RoHS, which increase efficiency of products, reduce human & environmental impact and energy bills in the long run.

2.6.3 Environmental Management Related to Eco-design

Eco-design is related and overlapped with other environmental management tools, thus the idea, focus, and importance of eco-design need to be rated. Pascual & Stevels (2004), stated that the implication of environmental management related to eco-design has two dimensions: (1) Environmental dimension – related to technicalities like physical units, materials, energy, efficiency, environmental load, and environmental validation; and (2)

Managerial dimension – related to business aspects of the discipline like goals and targets, EMAS, legislative requirements, and value chain management issues.

Further study of Pascual & Stevels (2004) on over 850 papers published in the electronics eco-design community conference e.g., IEEE/ISEE, Ecodesign, CARE Innovation, and Electronics Goes Green; shows that: A more managerial focus towards integrating eco-design considerations in the electronics industry is generally limited to discussion about environmental management systems, ISO standards, and of course EU legislation like EuP, WEEE and RoHS, leaving a side the wider stakeholder benefit issues and problems of successful management (value chain). In more than 60% of contributions at leading electronic oriented conferences that address technical issues such as LCA, materials, recycling, and lead-free soldering, about 10% address eco-design with traditional business perspectives, supply chain, EMS, green marketing, and etc.

Based on the evidences presented in the study it can be concluded that eco-design is more than the technicalities and drivers, which play a minor role when engaging eco-design in business contexts. Applications of eco-design within business context is still very limited and therefore requires more attention.

2.6.4 Now and the Future of Eco-design

Currently, the trend towards eco-design is being pushed more by the European, Energy-using Products (EuP) (Directive 2005/32/EC, 2005). This makes eco-design now an obligation for electronics products. The central manuscript for eco-design is the ISO Technical Report "Environmental management: Integrating environmental aspects into product design and development" (ISO 14062, 2001) links the workflow for product design and development with life-cycle thinking (see **Figure 2-14**).

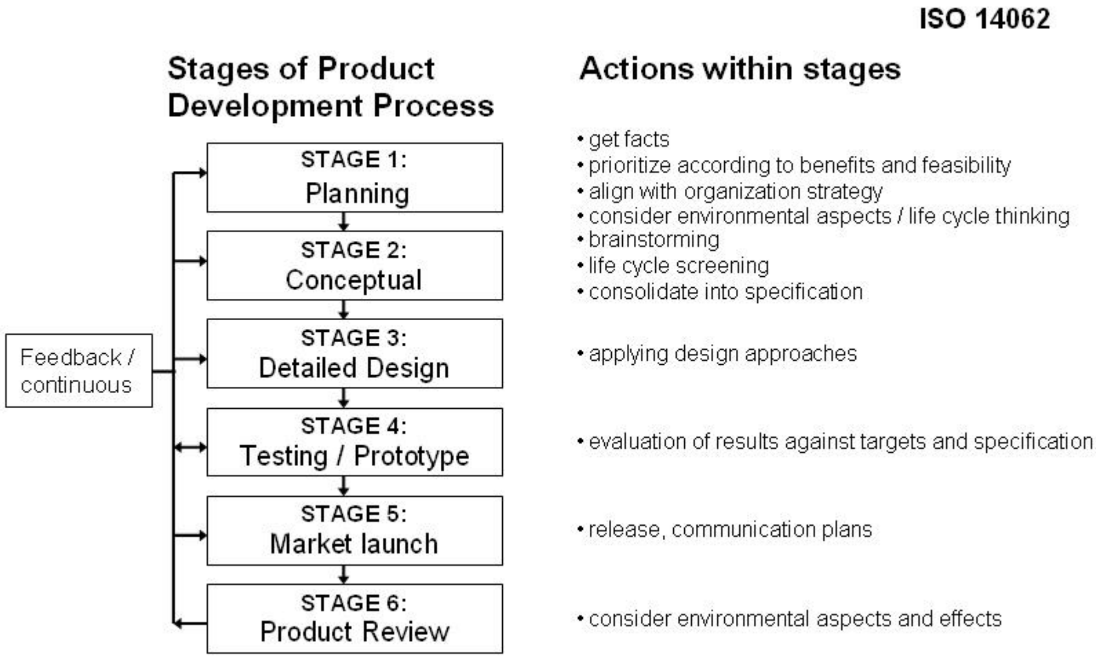


Figure 2-14: Generic model of integrating environmental aspects into the product development process according to ISO 14062.

From the figure, actions within the six stages have been listed and attached; the six stages are: (1) planning; (2) conceptual; (3) detailed design; (4) testing/prototyping; (5) market launch; and (6) product review. In many cases, it was found that the idea of eco-design, life-cycle assessment are missing after the market launch when the product is reviewed, it is suggested that these ideas should be put in place at the planning as well as the conceptual design stage. Eco-design can be considered as a proactive approach of systems thinking that lead to direct cost reductions, "customer benefit" as well as to environmental improvements, "social benefit" (Ecolife Network, 2002).

Generally, in evaluating a product for ecological and economical values; eco-design concept takes five key issues into consideration, e.g., (1) low costs, (2) high performance, (3) highly environmental friendly, (4) high reliability, and (5) high lifetime (see **Figure 2-15**).

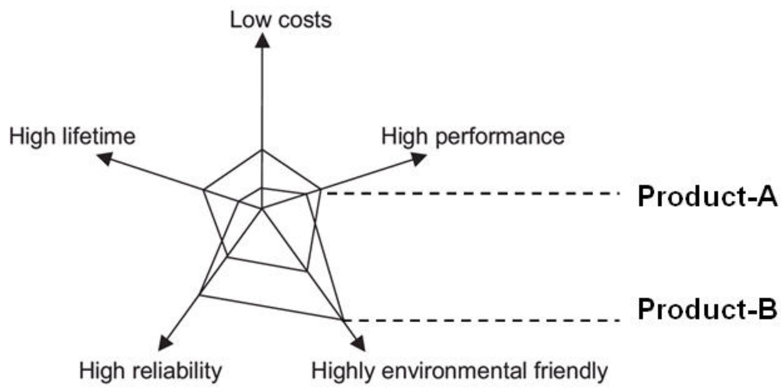


Figure 2-15: Quantitative relations between criteria (source: modified from Ong, 2004).

In this way, the product can be categorized and rated, thus enabling company internal activity for products benchmarking. In the figure Product-A has better lifetime, cost, and performance than Product-B, but in contrast it is poorer in environment-oriented design, and reliability, thus it is difficult to judge which product is better. Not all the five categories have the same unit which can be summed up together, unless they have been weighted (normalization) into a single score.

Future trend of eco-design; the development of systems thinking approach is expected to continue, from product improvement to productive system innovation (Ecolife Network, 2002). Ecolife Network (2002) has drawn the future development of eco-design into four levels (see also **Figure 2-16**):

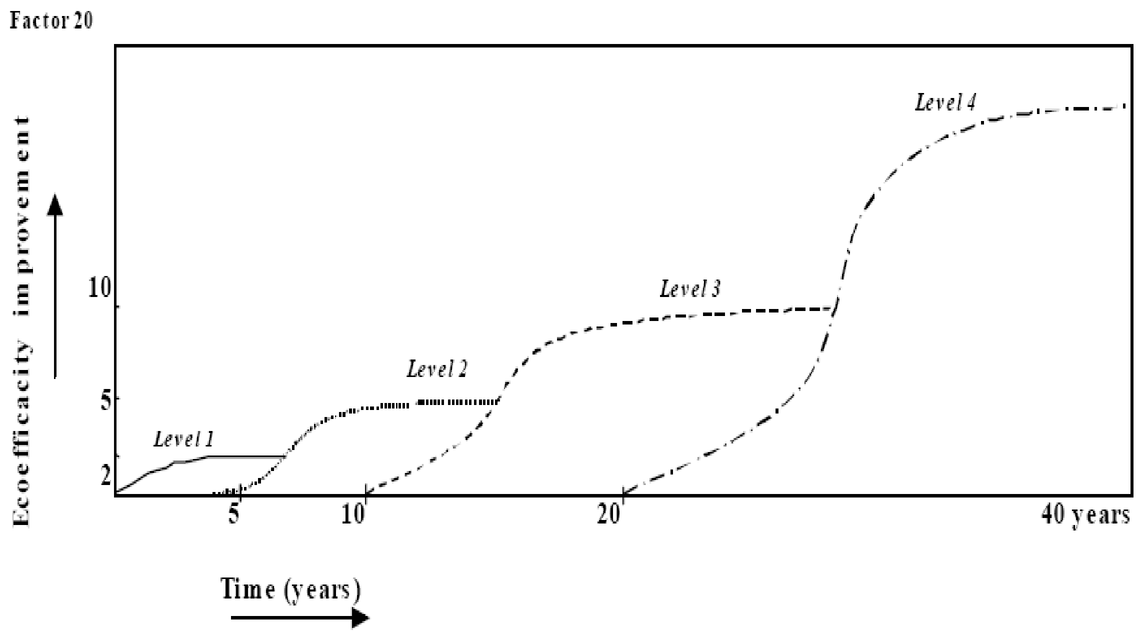


Figure 2-16: Four levels of eco-design (source: Stevels, 1996; Brezet, 1997, in Ecolife Network 2002)

Level-1. Product improvement, this is a progressive and incremental improvement of the product, a re-styling of the product; for example, it can consist of a decreasing use of materials or replacing one type of fastener by another.

Level-2. A new product is redesigned on the basis of an existing product.

Level-3. New product concept, comprises different innovation and technical functions for the new product with new functionality.

Level-4. New production system, occurs when innovation in the productive system is necessary.

The four eco-design levels giving the product development outlook and timelines, as of the technology nowadays moving rapidly on product development which is also being accelerated by several legislations, plus demands for innovative products have arisen dramatically; perhaps Level-4 of eco-design may come even faster, than the projected timelines.

2.6.5 Summary of Eco-design

Eco-design, which means the integration of environmental considerations at the design phase, is arguably the best way to improve the environmental performance of products. (EUROPA, 2005). Evidently, EuP (Directive 2005/32/EC, 2005) sets eco-design rules designed to reduce environmental harm, as well as save energy. The directive is expected to affect any company that wants to sell into the EU market of 400 million consumers as well as EU-based manufacturers (Spiegel, 2005). Since the market for electronics is now global, this scope effectively includes all major and most minor electronic product manufacturers, which are longer producing products individually designed to meet the rules of specific regions. Therefore, the knowledge of eco-design is essential for the global players for their environmental compliance policies.

2.7 Eco-efficiency

In 1991, the World Business Council for Sustainable Development (WBCSD) was looking for a single concept, to sum up the business end of sustainable development. It defined the term Eco-efficiency as… "Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth s estimated carrying capacity. In short, it is concerned with creating more value with less impact" (WBCSD, 2000). Eco-efficiency was developed as an internal tool at BASF in 1996 (BASF, 2003). The company uses eco-efficiency to achieve more value while lower inputs of materials and energy and with reduced emissions. Eco-efficiency is concerned with three main objectives:

1. *Reduce resource consumption*. To minimize energy, materials and land use, increase recyclability and/or durability of products, and loop-closing materials.
2. *Reduce environmental impact*. To minimize emissions, disposal; promotion of renewable resources.
3. *Enhance product or service value*. To enhance products or services functionality and flexibility.

The customer obtains the better functional need with fewer materials and less resources. However, eco-efficiency is not sustainability by itself because it focuses on the arena of economic and environment but does not embrace the society element. Most company prefers an assessment tool that can display product/process environmental loads against economic values. By plotting the relationship of product/service on ecological fingerprint (normalization) and cost (normalization), the position of product/service can be depicted in a certain frame. In fact, ecological fingerprints can be measured (categorized) by several indicators, however to simplify and to make it easy to present the results, six categories are selected. The six ecological fingerprint categories are: (1) emissions, (2) energy consumption, (3) toxicity potential, (4) risk potential, (5) land use, and (6) material consumption (see **Figure 2-17a**) (Wall, 2004).

In the past few years, eco-efficiency is widely used as one of the famous tools to compare different the ecological and economical aspects of the alternative product models. An example that applies the eco-efficiency for rating two alternatives is displayed in **Figure 2-17b**.

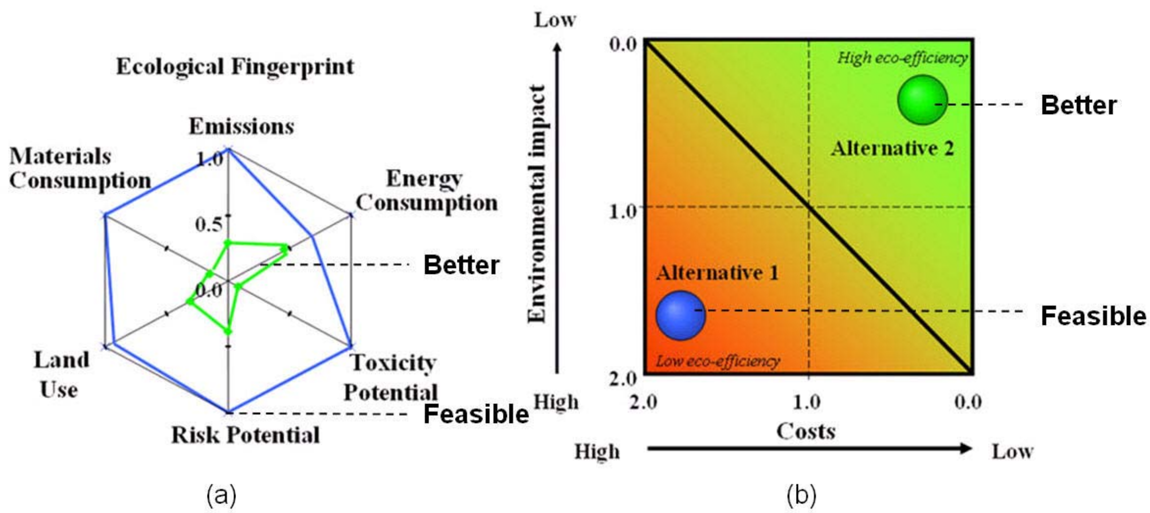


Figure 2-17: Using eco-efficiency to rate products: (a) Ecological Fingerprint; (b) Eco-efficiency (Environmental impact vs. Cost) (source: modified from Wall, 2004).

The result from the figure shows that, "Alternative-2" has a higher eco-efficiency (by average score) cheaper cost and lower environmental impacts (e.g., emissions, energy consumptions, toxicity potential, risk potential, land use, and material consumptions).

2.8 Life Cycle Assessment

> "Consumers are increasingly interested in the world behind the product they buy. Life cycle thinking implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all the relevant external effects. The impacts of all life cycle stages need to be considered comprehensively when taking informed decisions on production and consumption patterns, policies and management strategies." (Toepfer, 2003).

Life cycle assessment (LCA) is a tool designed mainly for assessing resources consumption, and environmental impacts over a product life span, starting from raw material extraction via product manufacture, use phase, and end-of-life management. In the context of international standards for life cycle assessment, ISO 14040-14043, are recognized worldwide and they give ideas of how to implement the LCA. A fundamental process of carry out LCA of product or process is to map out for inputs and outputs (see **Figure 2-18**).

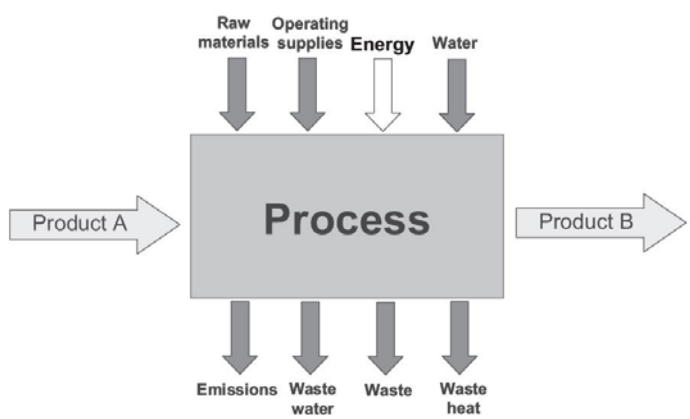


Figure 2-18: Map out process data (source: Nissen, 2004).

In the figure, a simple process is mapping out: (1) inputs e.g., Product-A, raw materials, operating supplies, energy, water, etc.; and (2) outputs e.g., Product-B, emissions, waste water, waste, waste heat, etc. These parameters are going to be: (1) evaluated; (2) make impact assessments; and (3) interpretation qualitatively and/or quantitatively for answering the study goals.

2.8.1 LCA Methodologies (ISO 14040-14043)

The basic LCA methodologies (steps) are as follow:

1. *Goal and scope definition* – define the study objectives (ISO 14040, 1997)
2. *Inventory analysis* – collect relevant information, subjected to impact categories, cost (ISO 14041, 1998)
3. *Impact assessment* – evaluate impact on human, environment by qualitative analysis and/or qualitative analysis (ISO 14042, 2000)
4. *Interpretation* – ensure the consistency and compatibility between goal and scope definition, inventory analysis and impact assessment, as well as illustrating hotspots and purpose for resolutions (ISO 14043, 2000)

The minimum requirement of LCA inventory is that it should meet at least the following criteria: quantitative, replicable, scientific, comprehensive, detail, peer reviewed, and useful (ISO 14041, 1998). When the study meets the requirement and when impact assessment is carried out, the interpretation could lead to the need to make product more environmental friendly and/or cost improvement choices could be found.

2.8.2 Environmental Labelling (ISO 14020-14024)

An environmental labelling will be awarded to products or services that complied with its criteria. In recent years, several developed and developing countries (e.g., WTO members) that are members of the Global Eco-labeling Network (GEN) have developed governmental and non-governmental voluntary eco-labeling schemes based on life-cycle approach. The eco-labeling from the country members of GEN and the year of its implementation are catalogued as following. Germany (1978); Canada (1988); Japan (1989); Nordic Countries: Sweden, Norway (1989), Iceland, Finland, Denmark (2000);

USA (1989), New Zealand, Sweden – Good Environmental Choice (1990); Austria, India (1991); European Commission, France, Korea, Netherlands, Singapore, Sweden – TCO Development, Taiwan/ROC (1992); Brazil, Croatia, Israel, Thailand (1993); China, Czech Republic, Hungary (1994); Indonesia (1995); Malaysia (1996); Hong Kong (2000); and Australia (2001) (WTO, 2003). They use their pre-set criteria on voluntary eco-labeling schemes, to evaluate products environmental performances through its life-cycle (ISO 14020, 2000; ISO 14024, 1999). Following extensive consultations, the pre-set criteria are being revised on regular basis to incorporate technological changes.

Various types of labeling schemes have been used for various purposes e.g., (1) Energy Star (US, EPA) takes only energy efficiency criteria into account; (2) TCO (Sweden) takes emissions, ergonomics, ecology and energy (as well as recycling) criteria into account (see **Figure 2-19**).

Figure 2-19: Environmental labelling (source: cataloged by Wongdeethai, 2002a).

Green Label (Thailand) considers various environmental concerns throughout products life-cycle including the efficient use of raw materials, energy, and reduction of wastes generation and environmental impacts (see **Figure 2-20**).

Figure 2-20: Eco-label (source: cataloged by Wongdeethai, 2002a).

The criteria are reviewed every two years. Similarly, other labels have individually combined life-cycle thinking and others are concerned with issues such as the environmental impacts, waste minimization, etc., in their particular scales. EcoMark (Japan), Nordic Swan (Nordic countries) and the Eco-label (Europe), is based on ISO14024. They consider the environmental impact of the products life-cycle from mining of resources to recycling of used products. The nomination of the environmental-label is awarded when the products meet its strict standards. The EcoMark, states that the product needs to make use of used plastics and recycled plastics, and at least 50% of the weight of the used product needs to be reusable or recyclable. The Eco-label or "Eco-flower" (European) scheme establishes environmental and performance criteria based largely on LCA study. For example, "criteria for obtaining the EU Eco-label for portable computers" (Commission Decision 2001/687/EC, 2001a; and 2001b) is described as follows. The criteria is valid until Aug. 2004 (see **Figure 2-21**).

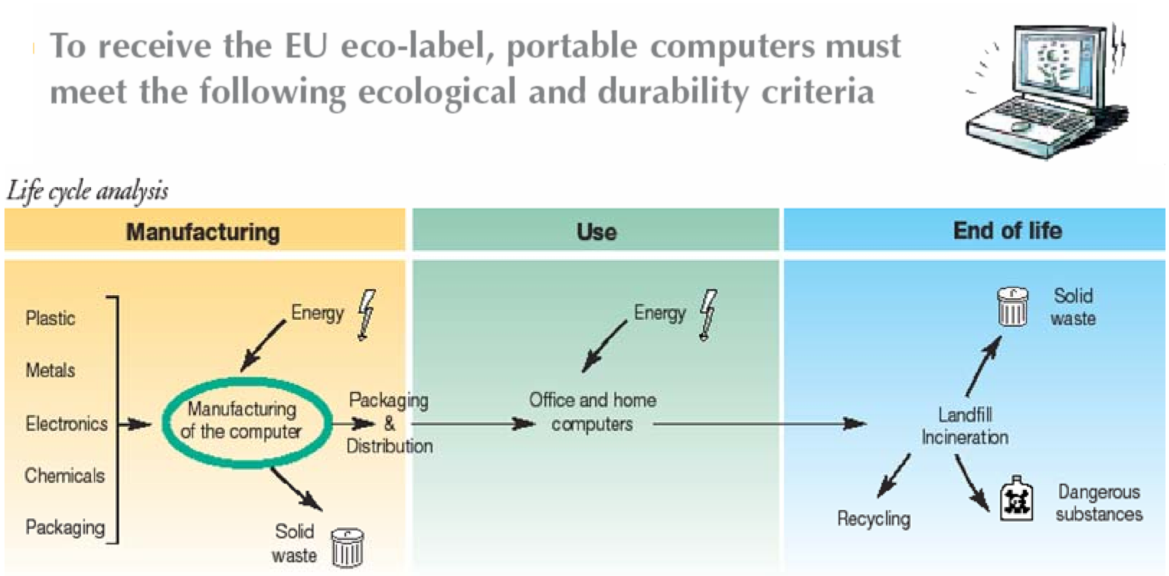


Figure 2-21: EU Eco-label for portable computer (source: Commission Decision 2001/687/EC. 2001b).

A product which fulfils both: (I) Ecological Criteria; and (II) Durability Criteria, will be awarded EU Eco-label.

(I) The EU Eco-label "Ecological Criteria" for portable computer are (see **Table 2-5**):

Table 2-5: EU Eco-label, Ecological Criteria (source: modified from Commission Decision 2001/687/EC, 2001b).

Limitation of the use of substances harmful for the environment and health
■ Plastic part heavier than 25g: • Restriction of the use of a list of flame retardants and those classified as carcinogenic, mutagenic, toxic for reproduction and dangerous for the environment according t Directive 67/548/EEC. ■ Heavy metal content in batteries (weight): • Hg: 0.0001% • Cd: 0.001% • Pb: 0.01% ■ Mercury content of the background lighting of a flat panels display: • 3 mg per lamp on average
Energy saving
■ Sleep mode state (suspend to RAM) < 5W. ■ Off-mode < 2W. ■ Change time by default: Operation to sleep ≤15 min. ■ Power supply < 1W when connected to electricity supply but not to computer
User instructions for environment use
The following information shall come with the product: • Use of power management features, disabling of features can increase consumption of energy and costs. • Availability of spare parts. • Ability of parts of the appliance to be recycled or reused. • Zero energy consumption if power supply is off or wall socket is switched off.
Noise levels:
■ ≤ 45 dB(A) in idle operating mode. ■ ≤ 55 dB(A) when accessing a disk drive.
Limited Electromagnetic emissions
As set in Council Recommendation 1999/519/EC
Durability
(see (II), below).
Reduction of ecological damage related to the use of natural resources by encouraging product recycling, maintainability and upgrading
■ Upgradability and exchangeability of some parts for some parts for the computer. ■ Easy dismantling and disassembling. ■ Recyclability of 90% (vol.) of plastics and metal materials used. ■ In plastic parts: • No lead or cadmium and metal inlays that cannot be separated. • One polymer or compatible polymers. • Permanent marking identifying the material.
Limitation of solid waste through take-back policy
■ Free of charge take-back For refurbishment or recycling of computer and components except for items contaminated by users. ■ Consumer information on take-back policy.

(II) The EU Eco-label "Durability Criteria" for portable computer are: (1) life time extension shall be guaranteed by the manufacturer through: (2) availability of compatible batteries and power supplies (3 years from cease of production); (3) functioning of the portable computer (3 years minimum from the date of delivery); (4) exchangeability shall be ensured for the memory, hard disk, CD drive or DVD drive; and (5) at least one socket available.

The new criteria for obtaining the EU Eco-label for portable computers (Commission Decision 2005/343/EC, 2005) brought slightly changes in: (1) mercury content; (2) reduced noise level; (3) reduced energy consumption; and (4) design to facilitate recycling [90% recyclable by volume, changed to 90% recyclable by weight]; as well as other minor changes.

To get a picture of, the differentiation among different kinds of eco-label? The comparison between the criteria of nine eco-labels are made. The "energy consumption of a monitor" is used as a basis for comparison between nine eco-labeling criteria (this criteria is common used by most eco-labels) (see **Table 2-6**).

Table 2-6: Low power consumption requirements for a monitor (source: AEA Technology, 2003; TCO Development, 2004).

No.	Scheme	Sleep mode (watts)	Deep sleep mode (watts)
1	EPA Energy Star	≤15	≤8
2	EU Eco-label	≤10	≤3
3	Nordic Swan Eco-label	≤15	≤8
4	Blue Angel Eco-label	≤10	≤5
5	Japan Eco-label	≤15	≤8
6	Korea Eco-label	≤10	≤10
7	Taiwan Eco-label	≤10	≤5
8	TCO 99	≤5	≤5
9	Australia Eco-label	≤10	≤5

This table shows that the energy consumption criteria used by the nine eco-labels are varied. Other criteria with different thresholds also exist but are not illustrated here. The criteria strict levels are largely depend on individual eco-labeling schemes.

2.8.3 LCA of Xenarc (Case Study)

How is LCA work? This case study summarizes how the company (OSRAM GmbH) commits to minimize ecological impact of relevant material and manufacturing procedures by using LCA for determination their products. The study focuses on the potential environmental impacts, waste, energy consumption during life-cycle of a high-intensity discharge lamp (Xenarc). Xenarc is the automotive headlamps which gives more lights (lumens) than traditional headlamps (cool-blue colour) but consumes less energy and produces less heat. The functional unit is 1,000 pieces of discharge lamp (D-Lamp) and all the life-cycle phases from raw material extraction, components manufacturing, assembly and test, use phase (average lamp life 2,000 h), and four end-of-life (EOL) scenarios were considered. The study aimed at examining and assessing the environmental merits of four end-of-life scenarios: (1) Landfill (taken as the reference); (2) Sorting of mixed valuable materials for recycling; (3) Incineration average standard; and (4) Incineration high standard. The overview of all processes (scope of the study) is displayed (see **Figure 2-22**).

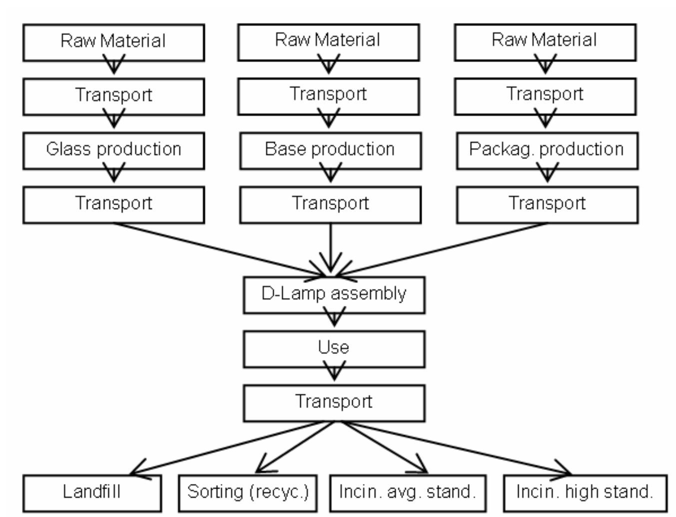


Figure 2-22: LCA of Xenarc (scope of the study) (source: Wongdeethai, 2004).

The scope of the LCA of Xenarc, has taken the following eight steps into account: (1) extraction of raw materials; (2) transport of raw materials to production plants; (3)

production of lamp main components: (i) glass (quartz), (ii) bases (plastics), and (iii) packaging (paper); (4) transport of lamp main components to the assembly plant; (5) production of lamp minor components, and manufacturing and assembly which yield products; (6) use phase; (7) transport of used D-Lamps; (8) end-of-life scenarios (with four possible destinations); (i) landfill, (ii) sorting of mixed valuable materials for recycle, (iii) incineration average standard; and (iv) incineration high standard.

In life cycle assessment, the main difficulty is to define the system boundaries. Theoretically, four field considerations have to be taken into account: (1) industrial process, (2) energy and its production, (3) substructures, and (4) human activities. Nevertheless, Boustead & Hancock (1981) demonstrate that the first two points on their own represent 95% of the whole energy cycle. Consequently, the two latter fields are usually omitted. Additionally, it should be noted that the influence of factory building would have been very small compared to the number of products produced. In relation to the transportation phases, the fabrication of the ships and trucks are neglected as well as the construction and maintenance of the roads. Only the energy consumption and the air emissions of the ships and trucks are considered. Concerning sorting of mixed valuable materials for recycling and incineration, the boundaries have to be defined in accordance with the definition of the functional unit. After recycling (incineration), recycled material (energy) is available. **Figure 2-23** presents the theoretical life cycle of the "System-1" (D-Lamp). If the k quantity of recycled material (energy) is used in the same application, the 1-k (energy) goes into another System, "System-2".

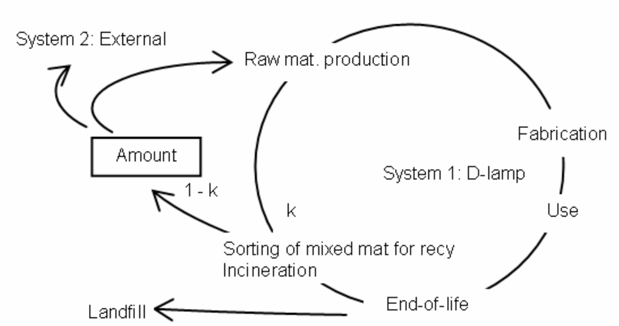


Figure 2-23: LCA of Xenarc (system boundary) (source: Wongdeethai, 2004).

The difficulty is to put the boundaries between the two systems and to isolate the system under study i.e., “System-1”. Generally, allocations between systems should be avoided by expanding the boundaries (ISO 14041, 1998). Various authors have introduced this concept of several functional units fulfilled by a system to take into account the productions of 1-k recycled material (energy) going into another system. Then the system is enlarged by adding subsystems that provide missing functions to relative alternative and consequently the functional unit is modified. This consideration is the most transparent and scientific (Le Borgne, 2001). Nonetheless, the growth of the system boundaries is virtually unmanageable, in particular when “System-2” is unknown. The added system increases the dimensions of the original system and does not facilitate the inventory calculation; in addition, it complicates the interpretation of the results.

Finnveden, G. (1994) has also proposed the use of allocation rules based on arbitrary numbers: between 0 and 100% of recycling is allocated to the studied system. This divides the environmental inputs and outputs associated with sorting of mixed valuable materials for recycling, or incinerations and is very subjective. Nevertheless, it can be considered that the 1-k quantity of recycled material (energy) represents a material (energy) amount and avoids somewhere in another system the consumption of virgin material (energy). Therefore, it does not matter on an environmental point of view the system within which the recycled material (energy) will be used. Consequently, a 100% allocation rules of the sorting of mixed valuable materials for recycling, or incinerating to the system-1 has been presumed, creating a closed loop. Note that this does not take into account the quality of loss of reused material due to the processing.

Specific onsite data collection of products & processes, documentations, and personals communications had been carried out for the data inventory, which had been using together with the software Umberto’s databank for the environmental impacts evaluation. Two evaluation methods provide by the software were selected: (1) the “CML” (Center Milieukunde Leiden) method, which follows the line of ISO; and (2) the “UBP” (Environmental Burden Points) method, which integrates a weighting of the impacts are used. The used of two different methods will allow comparison of the results and show whether they are method-dependant. The landfill has been taken as a reference and scaled to a value of 100 in both methods.

The environmental impacts results are illustrated in the figure (see **Figure 2-24**).

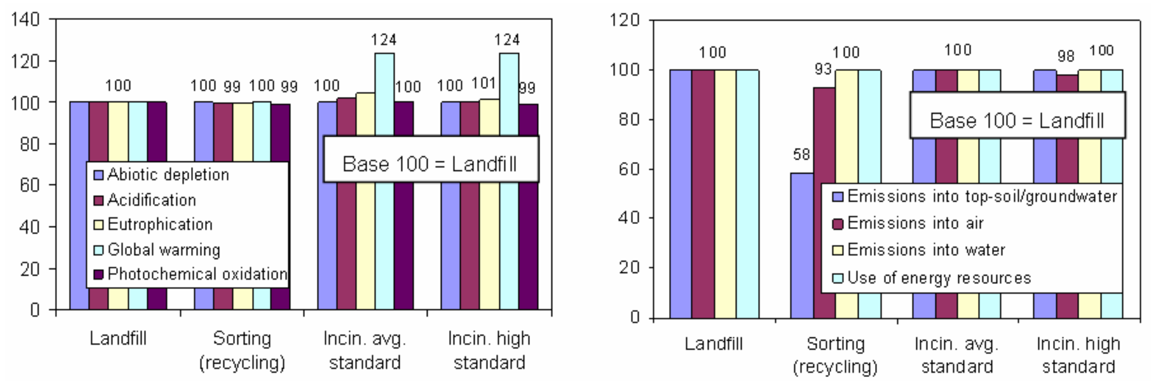


Figure 2-24: Impact results from CML method vs. UBP method, base 100 = landfill (source: Wongdeethai, 2004).

The reference quantities used for the two methods are: (1) Abiotic depletion basis 100 = 1.2 kg eq. Sb; (2) Acidification basis 100 = 0.86 kg eq. SO_2; (3) Eutrophication basis 100 = 0.06 kg eq. PO_4^{3-}; (4) GWP basis 100 = 91.54 kg eq. CO_2; (5) Photochemical oxidation basis 100 = 0.03 kg eq. Ethylene; (6) Emissions into top-soil/ groundwater basis 100 = 655 UBP; (7) Emissions into air basis 100 = 100.2 kUBP; (8) Emissions into water basis 100 = 598 UBP; and (9) Use of energy resources basis 100 = 1,912 UBP. [(1)-(5) refer to CML method; and (6)-(9) refer to UBP method].

By comparing both methods results, the conclusion points globally to the same direction, as the "Sorting of mixed valuable materials for recycling," is the best option, with the lowest average environmental impacts. From the product studied, it was concluded that there are no health or environmental risks from the lamp under normal operating conditions or even on the case of broken lamp. High-Intensity Discharge Lamps (HID Lamps) contain the sensitive mercury, but only in small amounts (Criens, unpublished; Metalle in der Umwelt, 1984). The issue of landfill, used products are regularly collected by authorized disposal companies, private consumers can give them to the collection systems in their municipalities to be disposed off as special waste in designated landfill site. At the selected EOL scenario: "Sorting of mixed valuable materials for recycling," residual materials, those that cannot be reused to manufacture lamps can be turned into "Foam Glass" in a new process (OSRAM, Publication). This Foam Glass can then be used as a versatile building material. The result is 0 % special waste.

2.8.4 Summary of LCA

Based on the results obtained from this case study (LCA of Xenarc) and with reference to automotive, LCA are powerful enough to evaluate from on environmental point of view various processes or technologies, including even costs considerations. It can be determined as a decision tool for strategic issues such as: the study of different EOL scenarios; emissions and environmental impacts during: material extraction, manufacturing, and energy consumption. Several product developers apply LCA at the products review stage and after the products have been launched into the market. It is recommended that LCA should be implemented earlier, at the planning stage, before conceptual and detailed design, owing to considerable data and time requirement.

2.9 Integrated Product Policy (IPP)

What is Integrated Product Policy? All products cause environmental degradation in some way, whether from their manufacturing, use or disposal. Integrated Product Policy (IPP) seeks to minimize these by looking at all phases of a products' life-cycle and taking action where it is most effective (EUROPA, 2005a). The goal of IPP is the continuous improvement of the environmental performance of products throughout their entire life cycle. Generally, over 80% of all product decisions with environmental-related issues and equipment are made during the product specification and design phases (Schroeder, 2004). IPP methodology is a combination of the cooperation of technical and political dimensions, based largely on three key principles as follows: (1) Communication – flow of information among stakeholders; (2) Cooperation – between participants toward objectives; and (3) Integration – environmental, economic, and social aspects through out the product life-span. IPP is thus use for this reason to extend industrial environmental protection. It is a tool designed to meet both environmental and business objectives at the same time (COM(2003) 302 final, 2003). This promotes a continuous improvement of the life-cycle of product and product related services, with the aim to minimize impact on human and the environment.

2.10 Trend towards Industrial Sustainability

Industrial sustainability means more than simply producing a “green” product; it comprises rather a wider perspective involving: society, economics, and environmental performance. In the environmental space concept: innovation, improvement, and use of cleaner technologies to reduce pollution levels and consumption of resources are the key elements, however, there are no concrete instructions on “how to get there.” A roadmap for industrial sustainability could go along with the famous pathways, for achieving sustainable development (see **Figure 2-25**).

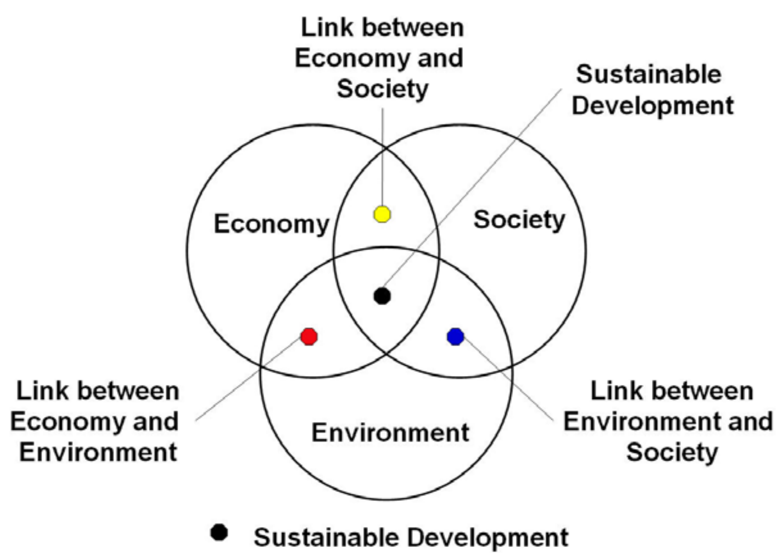


Figure 2-25: Sustainable Development (source: modified from CIRAIG, 2005).

Sustainable development (SD) is achieved when there is a compromise among: economy, society, and the environment, as displayed by the overlapping area innermost of the above figure. Other three interactions between each of two aspects (overlapping areas) i.e., (1) economy & society; (2) society & environment; and (3) environment & economy, are needed to resolve specific problems.

Industrial sustainability could not be possible without compromising and resolving the dynamic issues of politic, society, and advanced science and technology. These issues are influenced by the three main driving forces: (1) Government policy. Government policy responds to public pressure and enforces or encourages changes in manufacturing processes to meet strategic, environmental or social needs; (2) Economic competitiveness. Economic competitiveness leads companies to consider the advantages of products and processes management in terms of market niches or cost advantage; and (3) Scientific and technological feasibility. Scientific and technological feasibility proposes methodologies to deal with environmental problems e.g., waste treatment, end-of-pipe disposal, and remediation.

Natural capital (e.g., the natural resources and ecosystem services that make possible all economic activity, indeed all life) is scarce and limited, producers seek to better satisfy their customers' needs, increase profits, and help solve environmental problems all at the same time, e.g., by means of products innovation (Hawken, 1999). Technology-push and market-pull are fuelling the products innovation. Market pull is the link to market opportunities, while technology push is the technological competency, as well as the ability to transfer technologies into commercial capabilities. Market opportunities motivate entrepreneurs to seek solutions through exploiting technologies and capabilities, but enterprising technologies seek the market and creative value for their intellectual properties and proprietary products (Him, 2002; Verganti; Blakems, 2005).

Science and technology (e.g., Biotechnology & Nanotechnology) have strengthened a vast potential to move economies in Europe and around the globe towards a more sustainable development and improved quality of life. Europe cannot afford to miss the opportunity that these new sciences and technologies offer (COM(2001) 454 final, 2001; COM(2002) 27, 2002). Biotechnology is biological techniques applied to research and product development. In particular, the use of recombinant DNA, cell fusion, and bioprocessing techniques by the industry (Specialized encyclopedia & dictionaries). Another example of Biotechnology, Nanotechnology involve precisely controlling the morphology at nanoscale dimensions (usually 0.1-100 nm) of substances or particles to produce e.g., (1) Nanoelectronics, (2) Nanobiotechnology, and (3) Nanomaterials (EUROPA, 2005b). An OECD report (OECD, 1998) indicates that many manufacturing firms are unaware of the potential of biotechnology for cleaner production and improved efficiency and profitability. A new OECD report "The Application of Biotechnology to Industrial Sustainability," (OECD, 2005), cites actual case studies as proof that economic gains and respect for the environment can go hand in hand; new "bio-processes" can substantially reduce emissions and the use of hazardous raw materials, generate fewer waste materials and by-products, and consume less energy. The interaction between science and society poses a wide range of challenges (OECD, 1998); Life sciences and biotechnology are of strategic importance in Europe's quest to become a leading knowledge-based economy (COM(2001) 454 final, 2001). By incorporate these ideas where appropriate into SD concept e.g., products & processes, R&D, innovation, and other involving activities could sustain the system and improve the quality of life.

During the past few years, in the context of SD, the relationship among development, business (economic performance), and environmental protection (environmental performance) has evolved dramatically and continuous to get more and more attentions. This development has led to the following (1) compliance: manufacturing site permitting, waste tracking, and end-of-pipe controls; to (2) risk management (include compliance): EMS, material substitution, supplier selection; and expanding to (3) business & sustainable development (include compliance, and risk management): eco-efficiency, LCA (see **Figure 2-26**).

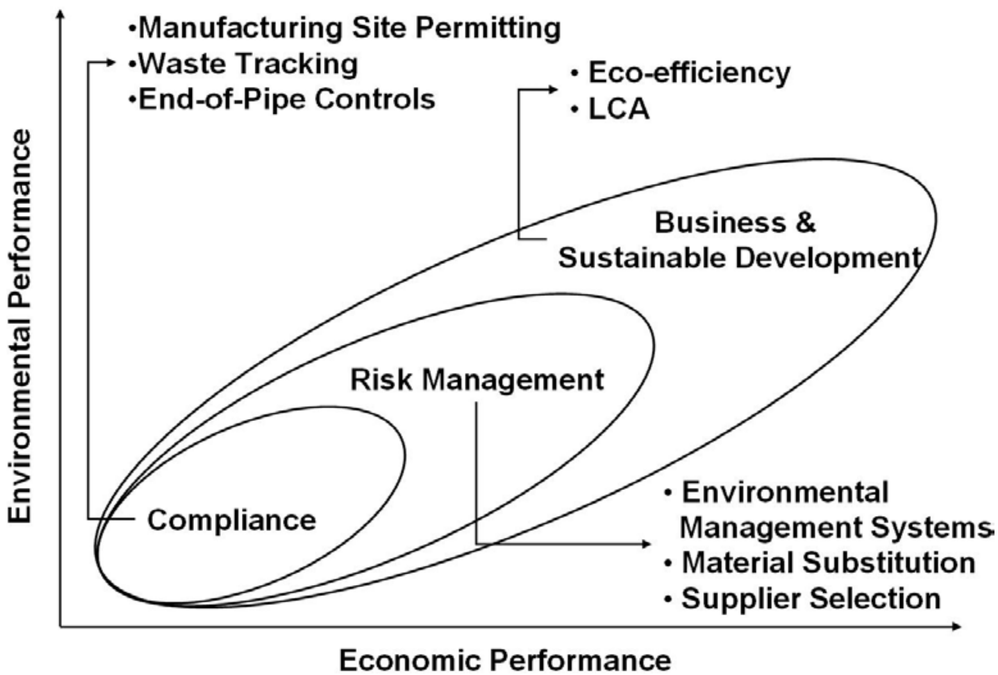


Figure 2-26: Trend in environmental strategy (source: modified from CIRIAG, 2005).

From the figure, the trend shows that industries do not just favour environmental compliance any longer; they adopt environmental strategies aiming at sustainability and sustainable development.

Looking at different perspective, and scale, the environmental interrelations can be observed and classified from different concern level (micro-macro) e.g., at single product lifetime, multiple manufacturers, and society (see **Figure 2-27**).

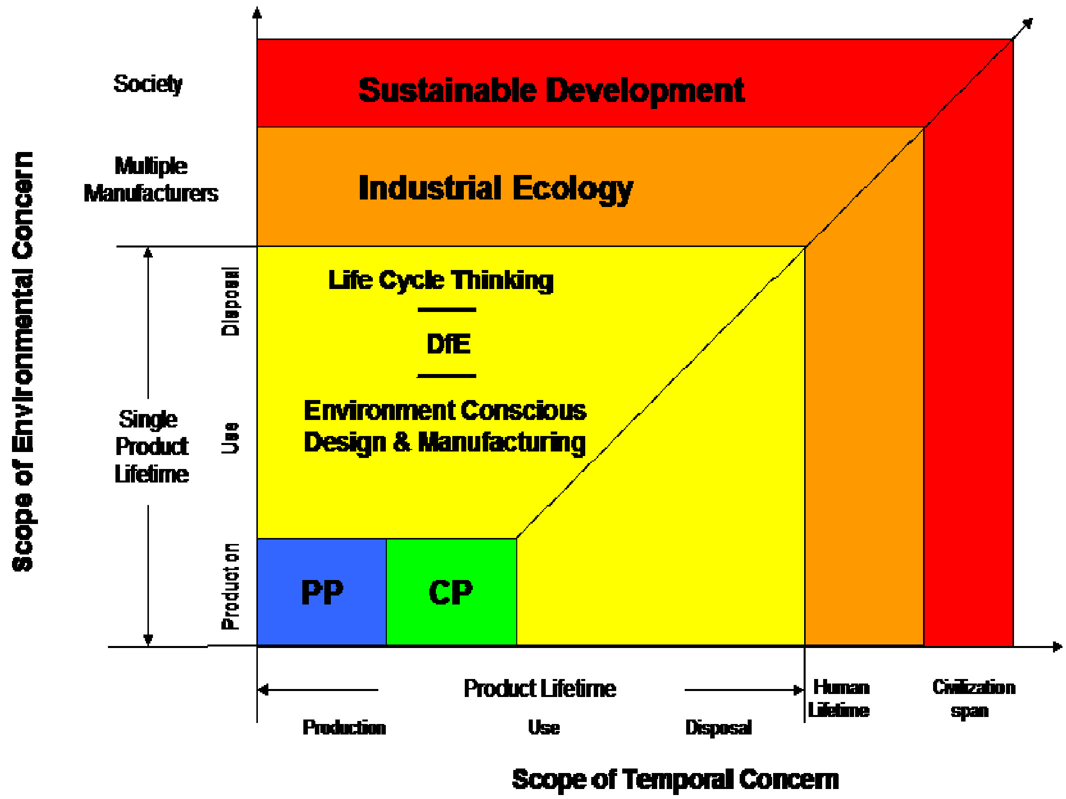


Figure 2-27: Moving toward sustainability (source: CIRIAG, 2005).

At single product lifetime, the focuses are on production-use-disposal-stage; pollution prevention (PP), and cleaner production (CP), are among the most effective ways to minimize environmental impacts at source, production-stage while life cycle thinking, DFE, and environmental conscious design & manufacture take the environmental concerned during production-use-disposal-stage. At multiple manufacturers' level, the concept of industrial ecology is used to minimize waste and environmental impacts. Above all, at societal level the concept of SD is used for industrial sustainability whilst maintaining societal responsibility and a secured environment.

Despite increasing awareness, in practice, there are a number of barriers to implementing industrial sustainability ideas. For example, it is unclear what industrial sustainability means in practical terms; business is often built on individual conviction or motivational cases, rather than being grounded in solid theory with associated frameworks, guidelines, and tools. The challenge for organizations include the choice of appropriate product and process technologies, lifecycle valuation techniques, appropriate tools, changing employee and other stakeholder mindsets, and possibly most importantly creating a new business model or sustainable-oriented society altogether.

2.11 Related Research Summary

Although, much progress has been accomplished in the last ten years, the final breakthrough towards sustainability has not been reached yet (Ertel, 2001). German Bundestag addresses in Protection of Humanity and the Environment – Objectives and General Conditions of Sustainable Development, that "The Study Commission shall continue the work of the Study Commission on Protection of Humanity and the Environment - Assessment Criteria and Prospects for Environmentally-Sound Product Cycles in Industrial Society" (Deutsche Bundestag, 2005). This focused on patterns and paths of development for the industrial society of the future. In order to facilitate sustainable development, it is necessary to design an appropriate economic, ecological and social framework and to examine the options for implementing it on national and international levels. Product-related environmental protection is a well-established goal within companies, beyond the legislatorial incentive; companies do care for environmental excellence to achieve economic and business advantages (Ertel, 2001). Environmentally friendly products and processes will consume less energy and raw materials and remarkably reduce or even eliminate waste. This means that all stages of products and processes are designed to reduce environmental impacts. Green products must be designed mainly according to their functions, environmental-oriented design, avoid temporary, fashionable styles (anti-fashion); and easily repaired, maintained and upgraded (anti-obsolescence) (Natural Step, 2003). Placing appropriate value on issues of environmental and social importance, managers may change company behaviour without neglecting their legal obligations and without changing the raison of most firms – to maximize both shareholder value and corporate profits, a "win-win-win" situation.

Chapter 3

Related Software

3.1 Introduction

A modern product and process development are infeasible without the assistance of computer tool. Simple spreadsheet programs/macros are no longer able to support, calculate and evaluate hundreds of sophisticate parameters, variables, and constraints of product/process units. This chapter reviews recent environmental management software available in the market, which are specific and up-to-date.

The latest versions, or fairly new versions of six softwares are reviewed. These are (1) DFMA – fully upgraded until 2002 (Boothroyd Dewhurst, Inc., USA); (2) GaBi 4.0 – the latest version 2005 (PE Product Engineering, IKP, Germany); (3) Umberto 5.0 – the latest version 2005 (ifu/ifeu, Germany); (4) TEAM – fully upgraded until 1997 (Ecobilan, France); a brand new (5) ProdTect 1.2 – the latest version 2005 (LCE Consulting/KERP Engineering); and the existence of (6) DEMROP – fully upgraded until 2000 (Siemens, Germany). These software are tested at the Department of Industrial Sustainability, BTU Cottbus, Germany. The last software which is reviewed: (7) euroMat (TU Berlin, Germany), at the time of writing, is not available at the Institute, therefore the software is reviewed based on its specifications. The reviews and opinions of the author expressed herein do not necessarily state or reflect those of the BTU Cottbus or the Department of Industrial Sustainability.

3.2 Software Overview

Three main criteria were used to select softwares from the market for review. The six softwares selected for reviewing are as follows: DFMA, GaBi 4.0, TEAM, Umberto 5.0, ProdTect 1.2, and DEMROP. Evaluation and comparison of the selected softwares were been carried out by using the following three criteria:

1. **Service**. The software (commercial) has been supported and updated including helpdesk and hotline services
2. **Functionality**. The software is run under Microsoft Windows® operation system environment; the process model size and complexity is almost unlimited; the software supports inventory and impact assessment; a graphical interface is implemented, a graphical process editor including import and export interfaces are provided
3. **Database**. (1) LCA softwares (e.g., Umberto, GaBi, TEAM) data of raw materials, power generation, transport and disposal are included; (2) DFX and Eco-design softwares (e.g., ProdTect, DEMROP) data of raw material, recycling cost, disposal cost are included; the data is based on European sources except DFMA for which data is based on American sources

The software overview and their affiliations according to the above three criteria are summarized and tabulated with respect to: name and address of the vendor, estimated price, software characteristics, and estimated number of users (see **Table 3-1**).

Table 3-1: LCA, DFX and Eco- design software overview.

No.	Software	Company/ address	Characteristic
1	**DFMA** (package with DFA, DFM, DFE, DFS) (developed over 35 years)	Boothroyd Dewhurst, Inc. 138 Main Street Wakefield, RI 02879 USA +1-401-783-5840 info@dfma.com http://dfma.com	**application:** DFA, DFM, DFE, DFS **price:** 37,000 € (consulting) **structure:** standalone or client server; developed with Delphi, Borland Local Internetbase, Server **functionality:** sophisticated **database:** very large **users:** more than 1,500 including Audi, Battelle, Bayer, BMW, Boeing, Bosch, Dell, Ericsson, Ford, GE Plastics, General Motors, Harley-Davidson, Mercedes Benz, Motorola, Nissan, Nokia, Rolls Royce, Siemens, Volkswagen, Volvo, and Xerox.
2	**GaBi 4.0** (package with SoFi and DfX) (developed over 15 years)	PE Europe GmbH c/o Mr.Daniel Coen Hauptstraße 111-113 70771 Leinfelden-Echterdingen, Germany +49-711-3418-1754 d.coen@pe-europe.com http://www.pe-product.de	**application:** LCA, LCC, DFE, DFR, IPP **price:** 10,000 € (professional) **structure:** standalone, web server, developed with Delphi, PHP **functionality:** highly sophisticated; Windows; Linux **database:** very large; MySQL, Oracle8i **users:** more than 500 including Bayer, DaimlerChrysler, Ford, General Motors, Motorola, Nokia, Siemens, Timberland, Unilever, and Volkswagen.
3	**TEAM 4.0** (package with DEAM database) (developed over 15 years)	Ecobilan Group c/o Jean-Michel Hèbert PricewaterhouseCoopers/ Ecobilan, Crystal Park 63, rue de Villiers 92200 Neuilly-sur-Seine, France jean-michel.hebert@fr.prc.com http://www.ecobalan.com	**application:** LCA, LCI, LCC, DFE, Policy making, waste management **price:** 23,000 € (consulting) **structure:** standalone, virtual client server installation using Objectstore **functionality:** highly sophisticated **database:** very large; additional data available **users:** more than 500 including AMPE, Alcatel, BMW, DaimlerChrysler, Ford, General Motors, Hewlett Packgard, IBM, Matsushita, Shell, Total, Toyota, Volkswagen, and Xerox.
4	**Umberto 5.0** (developed over 12 years)	ifu - Institut für Umweltinformatik ifu Hamburg GmbH Umberto Sales Große Bergstraße 219 22767 Hamburg, Germany +49-40-4800-090 info@ifu.com www.ifu.com www.umberto.de	**application:** LCA, LCC, LCI **price:** 500 € (educ), 6,600 € (business professional), 9,900 € (consulting) **structure:** standalone, or client server; developed with Delphi, Borland **functionality:** highly sophisticated **database:** very large **users:** more than 500 including BASF, DaimlerChrysler, DLR-German Aero Space, Fraunhofer-Institute, Procter & Gamble, OSRAM, Siemens, Volkswagen, Umweltbundesamt, and Yamatake Corporation.
5	**ProdTect 1.2** (developed over 15 years)	KERP Engineering Thomas Leitner Meldemannstraße 18 1200 Vienna, Austria Tel +43 1 93960/3070 Fax +43 1 93960/3079 t.leitner@kerp-engineering.com http://www.prodtect.com/	**application:** DFR, DFE **price:** 10,000 € (consulting) **structure:** standalone, server; developed with Java **functionality:** sophisticated **database:** medium, online recycling pass database **users:** more than 200 including LG, Electrolux, Blaunpunkt, Maga Steyr, University of Valencia, and University of Bayreuth.
6	**DEMROP** (discontinued in year 2000)	c/o Dr.W. Kasse Siemens Business Service GmbH, & Co.OHG SBS EBS S PDM Carl-Werg-Strasse 22 81739 Munich, Germany	**application:** DFR, DFE **price:** 4,000 € (consulting) **structure:** standalone **functionality:** sophisticated **database:** medium **users:** more than 150

3.3 Software Review

After reviewing the six softwares: DFMA, GaBi 4.0, TEAM, Umberto 5.0, ProdTect 1.2, and DEMROP all of them have the following functions and capacities in common:

1. **Hierarchical models.** Hierarchical models allow users to define a product/process and link different information from other scenarios/layers. This is very helpful when dealing with a complex product/process.
2. **Flexible library.** Flexible library allows users to store individual or customized processes in the library. These data sets can be treated in the same way as the original ones. It is possible to share them with other projects, computers or users.
3. **Parametric processes.** Parametric processes allow users to define specific values of product/process.
4. **Cost modeling.** Cost modeling allows users to calculate the total product/process price and to evaluate weak point/sensitivity analysis.
5. **System security.** Software producers' and users' confidential data and undisclosed information are loaded within the software, therefore the software security is vital and enable by a password and/or hard-lock (a password control system built on board, hardware e.g., PCB, USB, and Serial port).
6. **Import/Export.** Software supports data import and export e.g. to MS Excel, etc.
7. **Weak point analysis.** Weak point analysis assists users in identifying the most concern point within a complex product/process by comparing different models.
8. **Graphical presentation.** Graphical presentation presents overall inventory and impact data e.g., cost on company, society, environment; it is helpful for a quick and dirty presentation; detail analysis can be further investigated and displayed.
9. **Sankey diagrams.** Sankey diagrams is a graphical display of flows with respect to their quantities i.e., the greater the flow, the bigger the arrow thickness. Users can monitor and customize to display specific material or energy flows. ProdTect 1.2 and DEMROP do not provide this function.

10. **Add-in methods.** LCA software provides with predefined values on normalization and evaluation of impact criteria e.g., CML, UBA, Eco-Indicator and Ecological Scarcity. In addition, users can build new normalization methods (Add-in methods). DFR, DFX software rather fixes the method for calculating the concerned targets e.g., product performance, EOL cost, recycling rate, and recycling-orientation.

DFMA, GaBi 4.0, TEAM, Umberto 5.0, ProdTect 1.2, and DEMROP brief histories, concept ideas, features, and their applications are summarized based largely on the three following issues:

1. **Inventory database.** Inventory database is a compilation of inventories of backgrounds, literature reviews, experimental data results, onsite data collection, theories, methodologies, experts' opinions, legislations, and other valuable pieces of information. They provide documentation of the experimental results; methodologies used; actions of county, municipal governments, local court systems; the interactions within organizations and citizens. Not all information can be inventoried; database compilers only record the data specifically on their interested fields. This database is updated periodically as additional inventories are completed. Information found in the database includes detailed listings of series titles and date spans of permanent records as well as the name of the individual or organization that maintains the records.
2. **User interface.** User interface uses ten general principles for user interface design "Ten Usability Heuristics" described by J. Nielsen (2005) based on a factor analysis of 249 usability problems, as the basis of the review criteria. They are called "heuristics" because they are more in the nature of rules of thumb than specific usability guidelines e.g., (1) Visibility of system status; (2) Match between system and the real world; (3) User control and freedom; (4) Consistency and standards; (5) Error prevention; (6) Recognition rather than recall; (7) Flexibility and efficiency of use; (8) Aesthetic and minimalist design; (9) Help

users recognize, diagnose, and recover from errors; and (10) Help and documentation (Nielson 1994).

3. **Functionality.** Functionality is used to identify and verify that applications conformed to their specifications and correctly performs all required functions; variety of scenarios are tested to ensure that primary functions are working properly, and validated that all functions & outputs meet specified expectations.

Based on the above criteria, a short history; as well as my comment from tests of the six softwares on (1) inventory database, (2) user interface, and (3) functionality, are given, and described in the following sections.

3.3.1 DFMA

The Design for Manufacture and Assembly (DFM/A) was developed with more than 35 years of experience: DFMA-Method was developed by Dr. G. Boothroyd in 1975. Design for Assembly (DFA) was developed by Dr. W. Knigth and Dr. G. Boothroyd with industry consortium in 1977. Design for Manufacture (DFM) was developed by Dr. P. Dewhurst and Prof. Dr. G. Boothroyd with industry consortium in 1980. BDI Inc. released DFA Tool, the first version, in 1985, DFM Tool in 1988, DFA/PCB Tool in 1990, DFS Tool in 1992, DFE-Tool in 1992, and DFM Concurrent Costing in 2000 (Boothroyd, 2005). Boothroyd (2005) stated that the DFMA software is a combination of two complementary tools i.e., DFA & DFM.

1. *DFA software*. DFA software is used to reduce the complexity of a product by consolidating parts into elegant and multifunctional designs by: product simplification; competitive benchmarking tool; assembly cost and time estimation; and integration with DFM for total product cost (see **Figure 3-1**).
2. *DFM software*. DFM software allows the design engineer to quickly judge the cost of producing the new design and to compare it with the cost of producing the

original design by: early and accurate cost estimation; supplier negotiation and communication tool; process and material selection; and customizable.

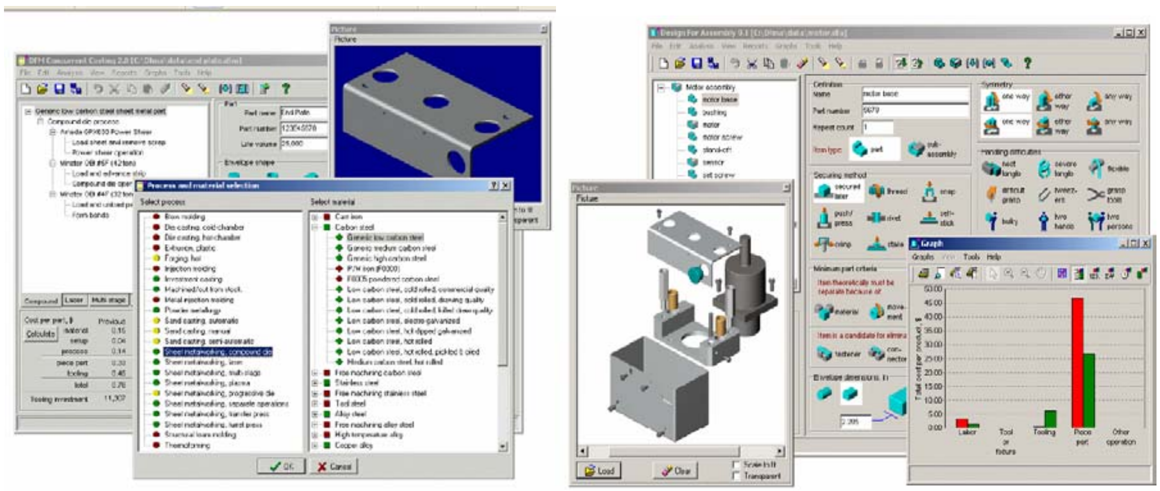


Figure 3-1: A sample of the screenshots of DFA software (source: BDI, 2005).

DFMA is used to slash down the assembly time/cost. The methodology is to ask key questions to build the product model. The key questions are: does the part need to be manipulated or oriented first? does the part need to be fastened, and what fastening operation is used, (press/snap etc)? is a separate operation needed to position the part? can the part be easily viewed, accessed, aligned and inserted? is the part sticky, sharp, fragile, or slippery and can it get tangled? is the part heavy and does it require tools or more than one person? is the part symmetrical about any axis? The answers provided by users to these questions (to some certain extent) make it possible for the software to build the product model. Further assessment and results can be obtained (Boothroyd, 2005).

1. *Inventory database* – materials and assembly time database.
2. *User interface* – logical and clearly arranged.
3. *Functionality* – its unique features are: client server architecture; the software can run in huge company networks; all information is stored in a central database; advanced import/export functionality CAD/CAM, (SolidView[9]); concurrent costing; and clear reports.

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[9] SolidView: a CAD/CAM software, can be used to import/export CAD/CAM files into/from DFMA.

3.3.2 GaBi 4.0

The software is developed by the cooperation between PE Product Engineering & the Institut für Kunststoffprüfung (IKP), University of Stuttgart. The first version was released in 1993, GaBi 4.0 in 2003. The GaBi 4.0 is fast and stable software, available in both English and German. GaBi 4.0 (software package with SoFi and DFX) are mainly used in areas e.g., LCA, LCE, MFA, SM, and DFR (GaBi, 2005). The expertise areas of the software package are displayed in **Figure 3-2**.

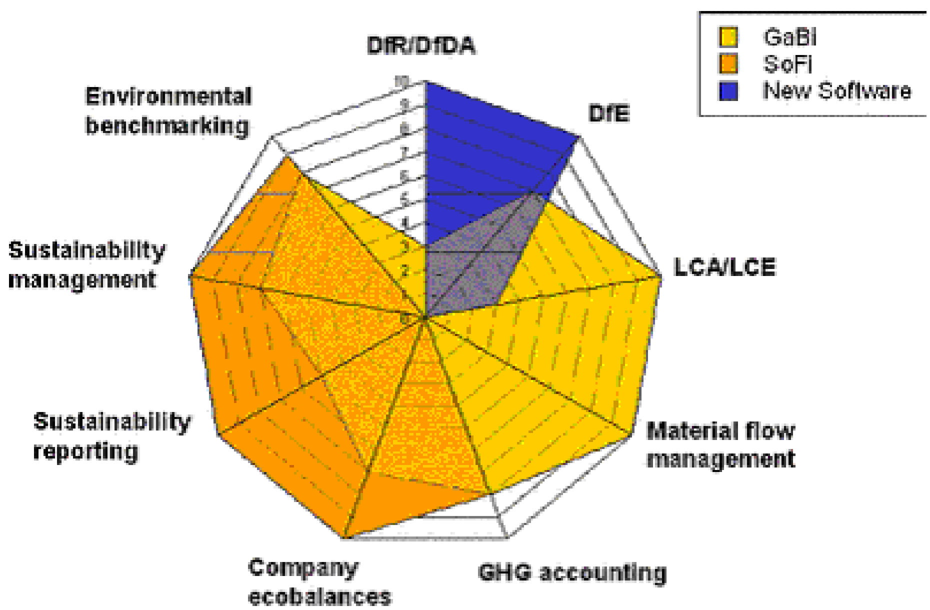


Figure 3-2: Gabi 4.0 software (source: PE Consulting Group, 2005).

1. *Inventory database* – with more than 1,200 modules (consult version). A unique feature is the inventory data for manufacturing processes e.g., casting, welding and grinning. Add-in function for new data.
2. *User interface* – user friendly, all program functions from modeling to graphical presentation can be called from this interface.
3. *Functionality* – good cost analysis; flexible handling of recycling processes; scenario analysis, sensitivity analysis; quality indicators; amendable units definitions; hierarchy modeling; graphic editor, search engine; and help & support.

3.3.3 TEAM

TEAM is the product of Ecobilan Group, France. The first version was released in 1993, TEAM 2.5 in 1998, TEAM 3.0 in 1998, and the latest version TEAM 4.0 in 2005 (TEAM, 2005). TEAM was the very first LCA software on the market which was suitable for evaluating complex products, now it has many competitors. TEAM is available in both English and Japanese. A sample of screenshots shows the user interface, database, and environmental impact evaluation (see **Figure 3-3**).

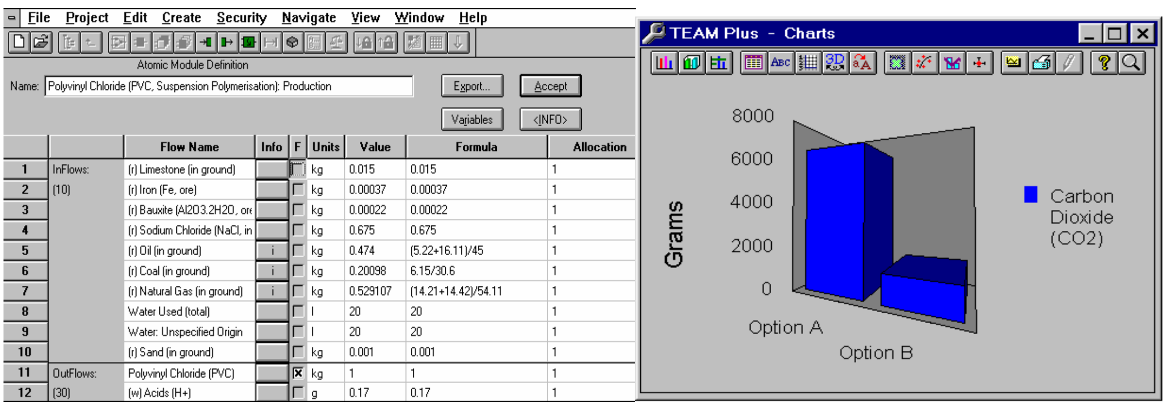


Figure 3-3: A sample of screenshots of TEAM (source: TEAM, 2005a)

1. *Inventory database* – with large database about 1,600 modules (consult version). The database does not focus on the manufacturing industry, data on chemicals and plastics are abundant, and the data is hardly documented.
2. *User interface* – the user-interface is a bit tricky. While the main functions are logical and clearly arranged, there are still many traps for the users. Problems are existed e.g., drag and drop, cut and paste to display text, well experienced users can handle these thus the capacity of the software is nearly not limited.
3. *Functionality* – network installation possible; hierarchical models and flexible library operations; display sophisticated graphical; scenario; sensitivity analysis; recycling processes; energy inputs; and very informative consistency checks.

Execute with rather low speed and unstable (shutdown), importing data into such a huge model is nearly impossible. Model management, unit definitions, parameters, and printing operations are way from perfection.

3.3.4 Umberto 5.0

Umberto is the LCA software, developed by ifu/ifeu [the Institut für Umweltinformatik (ifu), Hamburg and Institut für Energie- und Umweltforschung (ifeu), Heidelberg]. The first version was released in 1995, Umberto 3.0 in 1998, and Umberto 4.0 in December 2004. Any life-cycle network diagram can be drawn. Data of products, processes, and materials can be recalled, assigned and used from/to the software library thus balancing of the input-outputs and environmental impact can be calculated (see **Figure 3-4**).

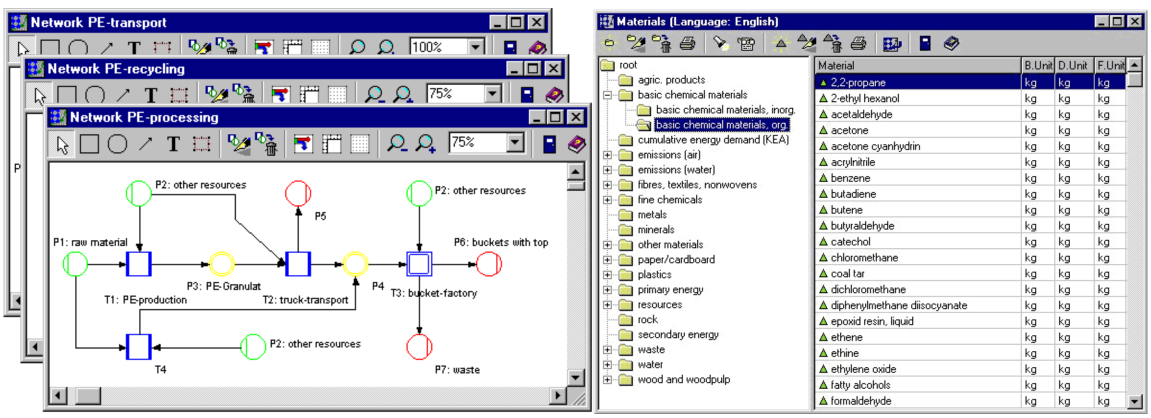


Figure 3-4: A sample of the screenshots of Umberto 5.0 (source: Umberto, 2005).

1. *Inventory database* – 1,200 modules in the consult version, focused on energy generation, many others on tensides, fertilizers, and natural materials, data on metals and manufacturing processes is rare.
2. *User interface* – user friendly, all program functions from modeling to graphical presentation can be called from this interface.
3. *Functionality* – customizable modules, at the installation stage; additional modules can be added at a later stage. Support hierarchical models, parametric processes and graphical presentation, library read and write all information is stored in a central database; flexible modeling (recycling loops); free definition of units; sophisticated costing system; sensitivity analysis; scenario analysis; cut and paste functionality; drag and drop; SQL interface; SPOLD import & export; graphic editor, and high quality Sankey diagrams.

3.3.5 ProdTect 1.2

LG-PRC cooperated with Technical University Braunschweig in Germany has first developed an eco-design tool "ATROiD." It is one of the most powerful and optimal tools for a company to cope with the EU WEEE and RoHS Directive. ATROiD version 1.0 and 2.0 had been used only for LG-Electronics from 1990 until 1995. In late 2001, LG-PRC launched ATROiD 3.0 into the market. Performance and stability have been improved in the new version and came up with a new name Product Architect (ProdTect) developed by LCE Consulting, Germany. ProdTect 1.1 was launched in 2004. ProdTect 1.2 was launch in 2005 by KERP Engineering, Austria.

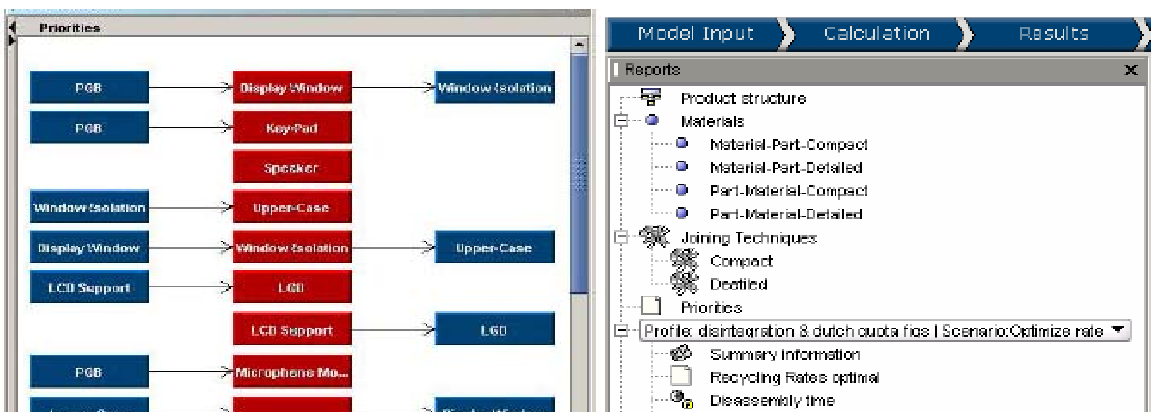


Figure 3-5: A sample of the screenshots of ProdTect 1.2 (source: KERP Engineering, 2005).

1. *Inventory database* – material, recycling, and disposal data are loaded.
2. *User interface* – user friendly, all program functions from modeling to graphical presentation can be called from this interface; customized windows integrate into the main windows; automatic resize best fit for all windows.
3. *Functionality* – unique features are: client server architecture; customizable models, simplify calculation in three steps (model input, calculation, and results); benchmarking; and clear reports.

ProdTect has been designed to simplify product data entry as much as possible. A sample of the screenshots (see **Figure 3-5**) displays a product structure; its materials and joining techniques used. ProdTect calculations are performed based on a product model, which holds all necessary details of the evaluated product.

3.3.6 DEMROP

Design Evaluation Method for the Recycling of Products (DEMROP) a software program commercialized by Siemens in 1997. It is one of the very first recycling software and most powerful at that time. DEMROP software system consists of three main components. First, a recycling knowledge base includes databases on materials, components, disassembly and process issues as well as market groups. Second, a product-modeling component comprises lists of parts and materials, enabling the creation of disassembly diagrams. Finally, a product evaluation component allows determination of recycling costs, disassembly strategies and recycling quotas. Users have overall control over database management, very flexible. A sample of the screenshots shows the user interface; a product disassembly analysis, and cost analysis results, which are displayed in bar graphs (see **Figure 3-6**).

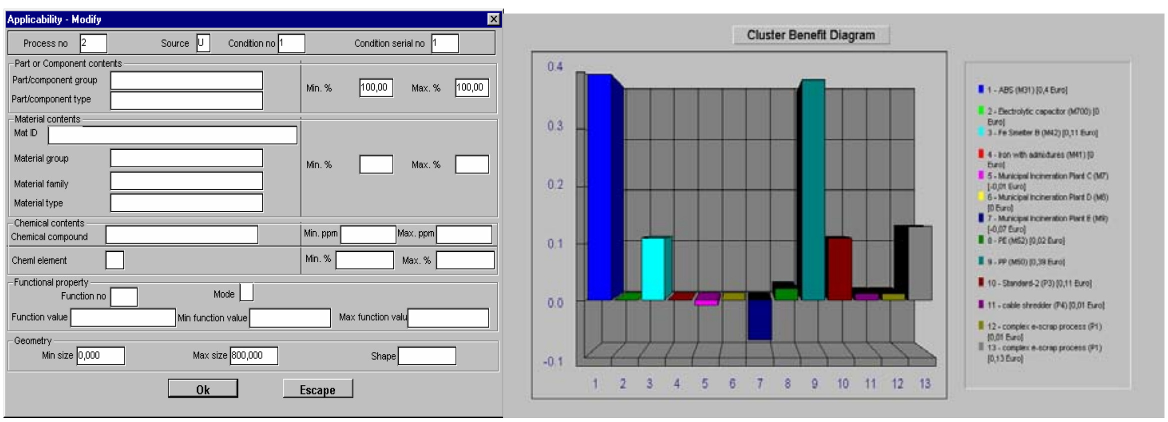


Figure 3-6: A sample of the screenshots of DEMROP (source: Kaase, 1998; unpublished).

1. *Inventory database* – material, recycling, and disposal data are available; users have free control over database.
2. *User interface* – user friendly, program functions can easily be called from this interface.
3. *Functionality* – unique features are: customizable models, data list import from CAD; benchmarking, disassembly graph, diagram, and clear report.

DEMROP product was discontinued in 2000.

3.3.7 euroMat

A brief information on software prototype "euroMat" supports engineering or industrial designer in the materials selection process of products. A sample of the screenshots displays the comprehensive multi-criteria assessment results of material options such as Magnesium, Steel, PP, ABS, and PA and related issues e.g., LCA, recycling, and risks (see **Figure 3-7**).

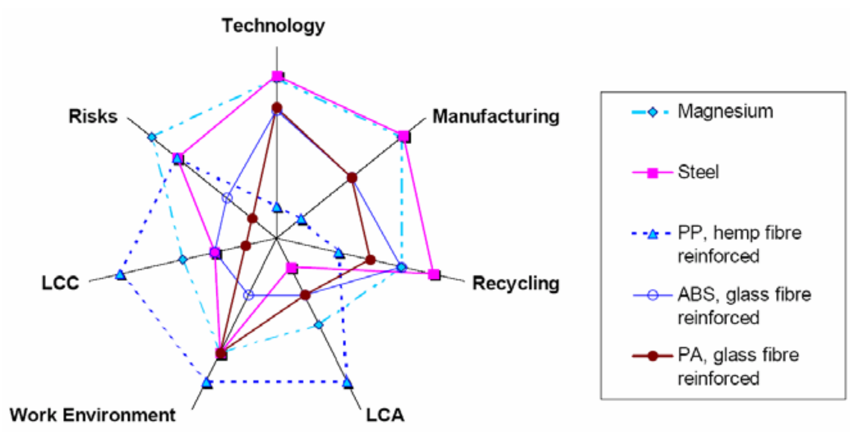


Figure 3-7: A sample of the screenshots of euroMat (source: Rebitzer, 2002).

This software is included in this section additionally. However, only the software overview is described, no further evaluation or test has been carried out.

euroMat goal is to find innovative materials for a given product, enhancing business competitiveness. Besides the conventional requirements, criteria of the sustainability paradigm are integrated. The euroMat methodology is administered by DLR (German Aero Space Center) and introduced by TU Berlin to resolve several case studies in order to validate the capabilities and practicality of the method. euroMat is sponsored by bmb+f, Ford, MAN Technology, BTU Cottbus, TU Berlin, Fraunhofer Institute, etc. (euroMat, 2004).

This tool and its methodology is not restricted to one specific branch, but rather gives decision support in all areas of industry. It does not only assist material selection but also focuses on joint types and assembly/disassembly sequence, and on areas such as technology, manufacturing, recycling, LCA, work environment, LCC, and risks.

3.4 Software Evaluation

DFMA, GaBi 4.0, Umberto 5.0, TEAM, ProdTect 1.2, and DEMROP, each has different capacities and specific applications, e.g., (1) DFMA is used mainly for product design applications, gives suggestions and simplifies the product model (eco-design); (2) GaBi 4.0, (3) Umberto 5.0, and (4) TEAM, is used mainly for LCA applications, for evaluating and assessing the environmental impacts of products and processes; while (5) ProdTect 1.2 and (6) DEMROP, is used mainly for disassembly analysis and design recommendations.

These proposed softwares are categorized, tested, and assigned the tasks with respect to their main functions, and particular applications. Three issues are considered: (1) product-oriented design, (2) environmental-oriented product design, and (3) recycling-oriented product design. Each software has been classified on its relevant applications regarding design characteristics, and main functions e.g., (i) DFM/A application [DFMA software], choices of material/product/process, models, product design, product structure, cost, and time are considered in the test to find the most effective product design. (ii) LCA application [GaBi 4.0, Umberto 5.0, and TEAM], the material/product/process were inventoried and evaluated; then carried out the impact assessment, results had been taken for recommendation and improvement analysis thus give the final reports. (iii) DFR application [ProdTect 1.2, and DEMROP], selection of product structures, materials, connections, avoidance of hazardous materials, design recommendation, and suitable EOL scenarios.

After the softwares had been categorized, tested, a certain evaluation method was necessary. This is subject to variation. Consequently, the detail results obtained which are sensitive shall not be disclosed. Hence, the portfolio analysis used instead of software rating format. The ratings are based on subjective impressions; others may come up with different findings. All the tested softwares were “consult version,” or equivalent, which different from their application versions. The software cost was roughly estimated by adding up the earliest version (first purchasing) until fully upgraded not only the software alone but also its database to the most recent version (information on test software versions, see **Section 3.1**).

My evaluation focused and described ten issues. These are: (1) Different tools and applications; (2) Equivalent version for comparison [consult version]; (3) Functionality; (4) Flexibility; (5) Database, the quantity and quality (regional context, up-to-date) of the process data are evaluated; (6) User-friendliness, takes into account if the interface is clearly arranged and allows time for effective work; (7) Software properties, stands for the stability, speed and hardware requirements of the tool; (8) Service, is the judgment as to whether support and updates are guaranteed; (9) Single score, rating (maximum = 100); and (10) Cost, reflects the sales price of the program. According to the results obtained from the tests. The outcomes have been tabulated (see **Table 3-2**).

Table 3-2: Evaluation of LCA, DFX and Eco-design software.

No.	Consult version	Functio -nality	Flexi-bility	Data-base	User friend-liness	Software properties	Service	Score	Cost T €
1	**DFMA** (DFA, DFM, DFE, DFS, DFX)	+ + + + +	+ + + +	+ + + +	+ + + + +	+ + + +	+ + + +	87	37
2	**Umberto 5.0** (LCA, LCC)	+ + + + +	+ + + +	+ + + +	+ + + +	+ + + +	+ + + + +	87	10
3	**Gabi 4.0** (LCA, DFE, DFR, DFX, IPP)	+ + + + +	+ + + +	+ + + +	+ + + +	+ + + +	+ + + +	83	10
4	**TEAM** (LCA, DFE)	+ + + + +	+ + + +	+ + +	+ + +	+ + + +	+ + +	73	23
5	**ProdTect 1.2** (DFR, DFE)	+ + +	+ + + +	+ + +	+ + + +	+ + + +	+ + +	70	10
6	**DEMROP** (DFR, DFE)	+ + +	+ + +	+ +	+ + +	+ + +	n.a.	47	4

n.a. = not available, T = thousand, software free trial or at reduced cost can be ordered, optional for educational purpose.

Each column in the table (e.g., Functionality, Flexibility, Database, User-friendliness, Software properties, and Service), has been rated by giving the positive sign ("+"), the more the number of positive signs the more acceptable (maximum = + + + + +). Later on, the six columns have been sum up and average, to give the final score. The Score {column}, the higher the score the more favourable the application. The software cost has been left out and not considered in this evaluation.

Evidently, (i) for DFM/A application [DFMA] obtained the highest score 87; (ii) for LCA application [Umberto] (among GaBi and TEAM) obtained the highest score 87; and (iii) for DFR application [ProdTect] obtained 70 scores. Based on their specific applications, users balance and pay attentions more to the need of functions and applications, and of course, the costs [see also, **Figure 1-2** for business decision making factors, **Table 3-2** for software overview (cost)].

3.5 Related Software Summary

The review has selectively chosen the six softwares for rating, in fact there are a number of other softwares available in the market, however the goal of the dissertation is not to name and examine them all but rather to have some ideas about: what kind of tools currently available, how they are being used, their applications and by whom.

According to the review results, DFMA, Umberto 5.0, GaBi 4.0, and ProdTect 1.2, are among most interesting LCA, DFX and Eco-design tools available on the market. The main advantages of these products are their sophisticated applications and functionalities that have the ability to display hierarchical models, parametric processes, cost (company, society, environmental aspects), which ease further evaluation (on products/processes) in presenting results.

Chapter 4

Integration Through Common Models

4.1 Introduction

In the previous chapters, related research and related software, have been presented including current available concepts, methodologies, guidelines, and tools, which are being used to increase economic, societal, and environmental performance of products. The development of modern management tools and their specific requirements for the assessment of recyclability of products has taken these concept ideas and integrated relevant issues into common models, to elucidate sustainable development solutions. The main concepts of previous related research and related software are summarized in the following sections. Relevant issues are considered, elaborated, highlighted, and integrated into the conceptual ideas of this dissertation.

4.2 Data Integration

Various relevant concepts from related research and related software, were collected and assembled into common models, which afterwards were configured and integrated into a new structure. Conceptual ideas of these related research and related software, contributed both direct and indirect information for building common models. The underlying common models contain architecture models. The architecture model refers to the model of computation, which represents the concurrency at both the instruction set and the microarchitecture levels. It defines how the architectural or microarchitectural components operate and how they interact with each other, which is the key execution semantics of a determination process. Therefore, this dissertation views the architecture model as the most important factor that underscores the quality of ReOAT. Nevertheless, it is not intended to load all bulky collected/produced information, or hundreds lines of source code into the dissertation body. Essentially, the focused is on the theoretical and assumption perspectives, on background information, how it is made, how it works, and benefits that could be obtained from this work.

The ReOAT's concept, and related research concept i.e., 3R, Industrial Ecology (IE), Product Design, Design for Manufacture and Assembly (DFM/A), Design for Recycling (DFR), Design for Environment (DFE), Eco-efficiency, Eco-design (product design for sustainability), Life Cycle Assessment (LCA), Integrated Product Policy (IPP), and Trend towards Industrial Sustainability are compared and tabulated as follows (see **Table 4-1**).

Table 4-1: ReOAT's concept vs. related research's concept.

No.	Name of Related Research	Related Research's Concept	ReOAT's Concept
1	**3R**	reduce, reuse, recycling (see **Section 2.2**)	reduce, reuse, recycling goals have been taken into account
2	**Industrial Ecology**	influences of economic, political, regulatory and social factors on flow of materials, use and transformation of resources (see **Section 2.3**)	reduce waste generation, reduce use of raw material, avoid use of hazardous material, material loop-closing
3	**Product Design**	design concept: reduce material, increase functionality, cheaper the cost (see **Section 2.4**)	"green" product design concept is preferred and has been taken into account
4	**DFMA**	reduce assembling (dismantling) and manufacturing cost and time while increase the benefit (see **Section 2.5.1**)	reduce disassembly time
5	**DFR**	design product ease for recycling (see **Section 2.5.2**)	simplify product structure, ease for disassembly, preferred the use of recycle material
6	**DFE**	design product on environmental-oriented basis (see **Section 2.5.3**)	less hazardous material use, recycling material is preferred
7	**Eco-design**	reduce the environmental load of product from "cradle-to-grave" (see **Section 2.6**)	complement to Eco-design's concept
8	**Eco-efficiency**	rating of product performance, cost, and ecological impacts (see **Section 2.7**)	rating recycling-oriented product design, product performance, and cost
9	**LCA**	assessing environmental impacts through out the product life cycle, cost analysis (see **Section 2.8**)	complement to LCA's concept
10	**IPP**	continue improvement of the environmental performance for product throughout its entire life (see **Section 2.9**)	complement to IPP's concept
11	**Trend towards Industrial Sustainability**	pollution prevention, cleaner technology, innovative product/process, intelligent material, life-cycle thinking, economy, ecology, policy (see **Section 2.10**)	facilitate product recycling-oriented assessment, regulation conformity, and economic competitiveness

The ReOAT's concept, and related software concept e.g., DFM/A software [DFMA], LCA software [Umberto, GaBi, TEAM], DFR/E Software [ProdTect, DEMROP] are compared and tabulated as follows (see **Table 4-2**).

Table 4-2: ReOAT's concept vs. related software's concept.

No.	Name of Related Software	Related Software's Concept	ReOAT's Concept
1	**DFM/A software** [DFMA]	design to reduce assembling (dismantling) and manufacturing cost and time while increase the benefit (see **Section 3.3.1**)	reduce part, material, joint type, facilitate dismantling (assembling)
2	**LCA software** [Umberto, GaBi, TEAM]	model, calculate and visualize material and energy flow systems; analyze the process systems, along a product life cycle, assess economic and environmental performance (see **Section 3.3.4**, **Section 3.3.2**, **Section 3.3.3**)	reduce number of parts, materials, joint types, thus reduce the flow of materials in the system; facilitate dismantling (assembling) at EOL of product
3	**DFR/E Software** [ProdTect, DEMROP]	model product, examine EOL phase, visualize cost at design stage (see **Section 3.3.5**, **Section 3.3.6**)	product design, demonstrate product EOL cost & performance

4.3 Common Models

ReOAT system has integrated infrastructure models from design to support that built mainly on Visual Basic (Visual Studio .NET 2003). It creates an infrastructure that is based on related research and related software concepts by simplifying development and management, and integrated innovation by anticipating needs and opportunities. The conceptual idea (goal and scope) was developed and improved with time to design the front-end model (see **Figure 4-1**).

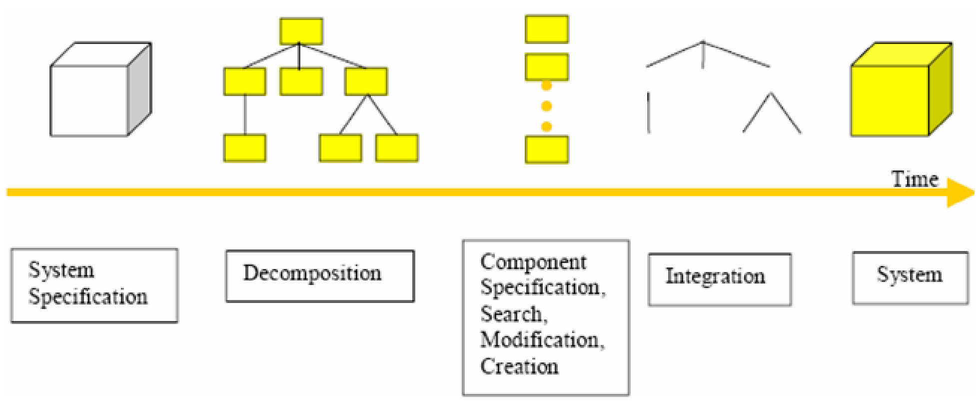


Figure 4-1: Design front-end model (source: Dogru, 2000).

The initial software goal and specifications have been disintegrated, reconsidered, modified, and restructured. The core ideas and factors needed were identified, relevant factors and constraints were incorporated, and provided e.g., various types of data use, regulations involved. The cross-functions were defined and connected between models.

Form the figure, the core application definition and programming model were considered as the foundation for the application's infrastructure. Each model consists of navigation bars such as menu, sub-menus (drop-down menus), modules and elements. It accommodates and merges similar properties and functionalities set together, which are user-friendly and feasible for further recall. The ReOAT's system gives access to models and support functions. The menu fields can be selected by mouse click on the fields. The drop-down (pull-down) menu displays more details/options, which can also be selected by mouse click. The system comprises of eight models: (1) Master model, (2) Material model, (3) Joint model, (4) Profit model, (5) Product model, (6) Window model, (7) Help model, and (8) Report model, (see **Figure 4-2**). These models and its functions are described in the following sections.

Figure 4-2: ReOAT system consists of eight models.

ReOAT System: Command Explanation
{use throughout in **Chapter 4** and **Chapter 5**}

Example:
[Master] – model, means *Master model*.
[Country], means sub-menu named *Country*.
[Master] – model > (Country), means clicking at the *Master model* (or pull down the menu) and choose *Country* (select menu element).

4.4 Master Model

The [Master] – model, provides projects basic information e.g., owner/user name, contact address, country of origin, currency, and wage per hour, which can be categorized into two menu elements: (1) [Country], and (2) [System Control] (see **Figure 4-3**). Within *Master model* is situated an [Exit] option, where users can leave and close the program properly, by clicking [Exit].

Figure 4-3: [Master] – model.

4.4.1 Country

The [Country], indicates the country of origin of project and the wage per hour with regard to its currency, e.g., USA (USD, $), European Union (EUR, €), Thailand (THB, ฿), and Japan (JPY, ¥) (see **Figure 4-4**). The [Country] data, can be added/modified/deleted by using *Add, Edit,* and *Delete* button located on the top of the window. Any labor cost/hour can be assigned.

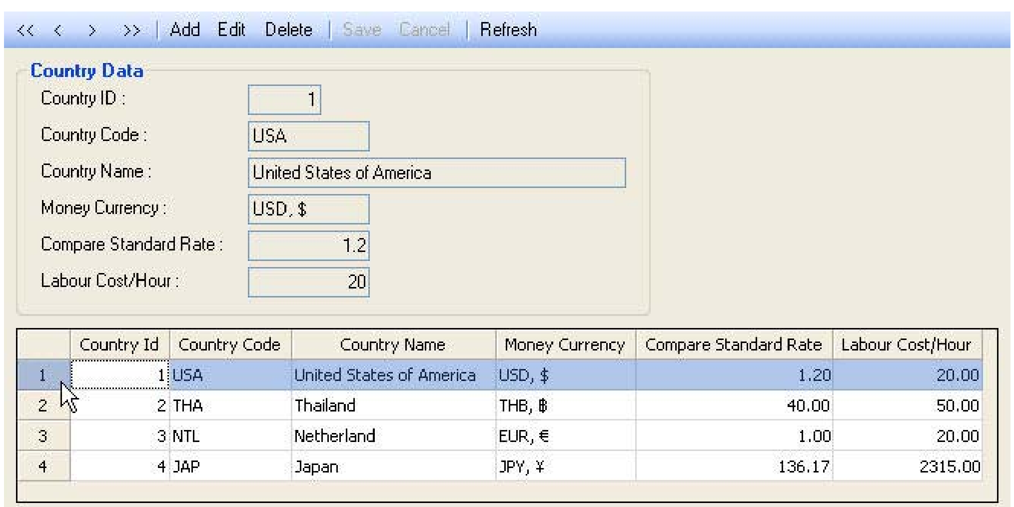


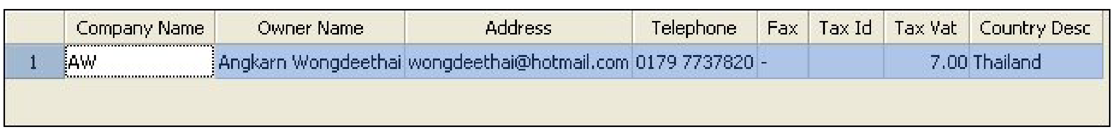
Figure 4-4: [Master] – model > (Country).

ReOAT System: Note

For all cases (for other menus as well), make sure there is the need for database modification before triggering *Add, Edit* or *Delete* buttons, because when data are modified they will be overwritten and can not be retrieved.

4.4.2 System Control

The [System Control], displays details of last updated particulars of the project owner e.g., *Company Name, Owner Name, Address, Telephone, Fax, Tax ID, Tax VAT,* and *Country of origin*. This information can be saved, edited, and recalled at demand (see **Figure 4-5**).



	Company Name	Owner Name	Address	Telephone	Fax	Tax Id	Tax Vat	Country Desc
1	AW	Angkarn Wongdeethai	wongdeethai@hotmail.com	0179 7737820	-		7.00	Thailand

Figure 4-5: [Master] – model > (System Control).

4.5 Material Model

The [*Material*] – model, provides material information for the project, it consists of three menu elements: (1) [Material Type], (2) [Categories], and (3) [Material] (see **Figure 4-6**).

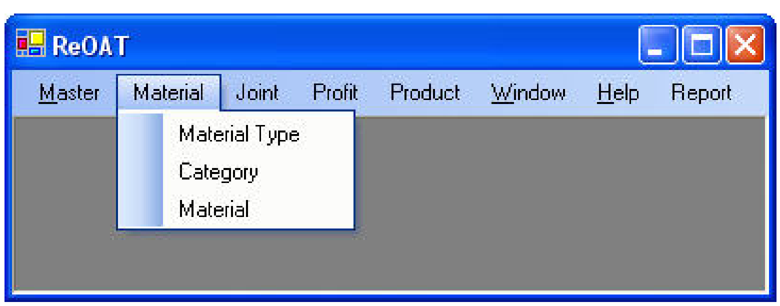


Figure 4-6: [Material] – model.

4.5.1 Material Type

The [Material Type], provides material type's information e.g., *Material Type ID, Material Type Code,* and *Material Type Name* (see **Figure 4-7**).

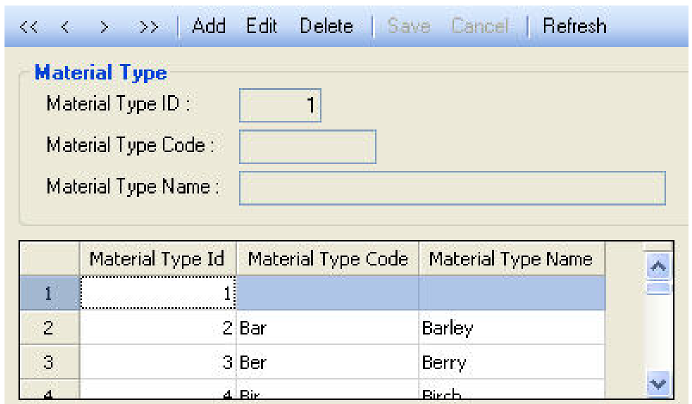


Figure 4-7: [Material] – model > (Material Type).

The *Material Type* data can be added/modified/deleted by using *Add, Edit,* and *Delete* button located on the top of the window. Any material type code/name can be assigned. *Material types* (*Name, Code*) are practically useful to identify and differentiate type of materials in detail, when the names or sub family names of materials are similar, the material types can be distinguished e.g., Metal, Plastic, or PCB.

4.5.2 Category

The [Category], provides category's information such as *Category ID, Category Code,* and *Category Name* which can be added, edited, and deleted, individually with respect to each database category. A family-category tree accommodates child-category materials, which have similar basic properties. Typically, a family-category of materials usually has a single or shorter name than its child-category e.g., (1) Aluminium, Magnesium, Tungsten, and Polyethylene are family-category; (2) Aluminium Sheet, Magnesium Nickel, Tungsten Pure, and Polyethylene HDPE are child-category. Similar materials can be group into one particular name (family-category), that gives a rough idea of what kind of materials could be its child-category. Well-structured family tree, systematically categorized materials and information, that eases further recall, locate, adjust, and update (see **Figure 4-8**).

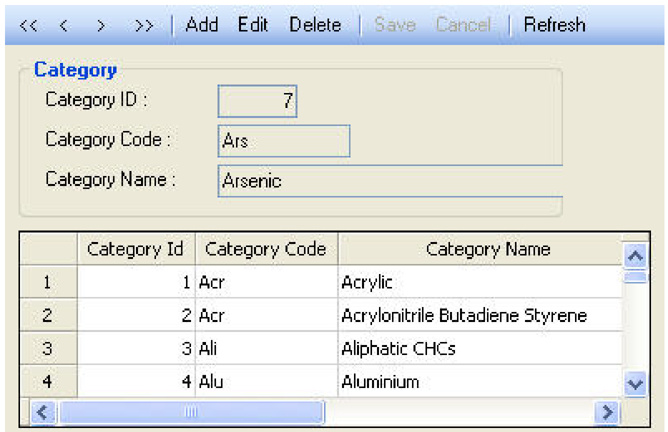
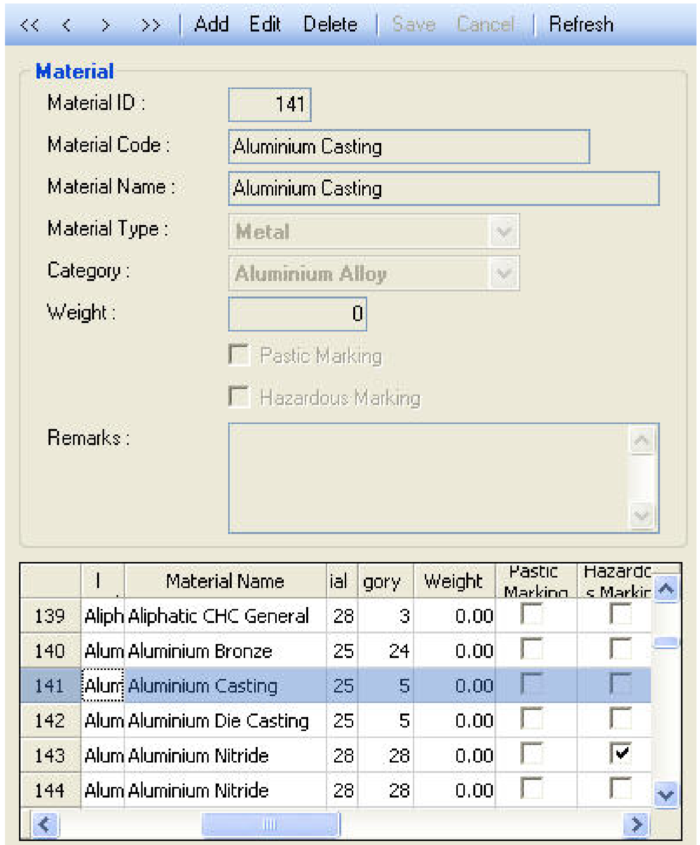


Figure 4-8: [Material] – model > (Category).

The *Category* data can be added/modified/deleted by using *Add, Edit,* and *Delete* button located on the top of the window.

4.5.3 Material

The [Material], contains all necessary information of materials e.g., *Material ID, Material Code, Material Name, Material Type, Category, Weight, Plastic Marking, Hazardous Marking,* and *Remarks* which can be added, edited, and deleted each material database individually. The [Material], helps to identify child-category of materials that are slightly different in names e.g., (1) Aluminium (Bronze), (2) Aluminium (Casting), and (3) Aluminium (Die Casting). By using [Material], materials' names and properties can then be clearly distinguished. This increases the accuracy of information when recall from the database (see **Figure 4-9**).



	I	Material Name	ial	gory	Weight	Pastic Marking	Hazardous Markir
139	Aliph	Aliphatic CHC General	28	3	0.00	☐	☐
140	Alum	Aluminium Bronze	25	24	0.00	☐	☐
141	Alum	Aluminium Casting	25	5	0.00	☐	☐
142	Alum	Aluminium Die Casting	25	5	0.00	☐	☐
143	Alum	Aluminium Nitride	28	28	0.00	☐	☑
144	Alum	Aluminium Nitride	28	28	0.00	☐	☐

Figure 4-9: [Material] – model > (Material).

4.6 Joint Model

The [Joint] – model, contains necessary information on connection mechanisms of items that can be recalled within the project; it consists of four menu elements: (1) [Joint Type], (2) [Disassembly Type], (3) [Disassembly Tool], and (4) [Disassembly Time] (see **Figure 4-10**).

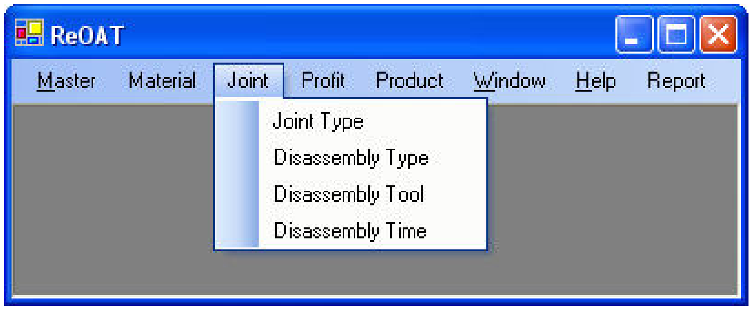


Figure 4-10: [Joint] – model.

4.6.1 Joint Type

The [Joint Type], contains necessary information on connection types e.g., *Joint Type ID, Joint Type Code, Joint Types,* and *Specification* (see **Figure 4-11**).

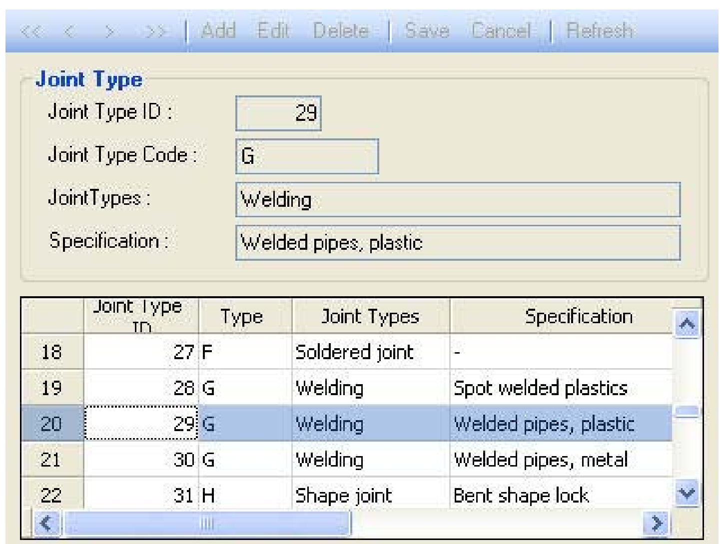


Figure 4-11: [Joint] – model > (Joint Type).

4.6.2 Disassembly Type

The [Disassembly Type], contains necessary information on disassembly types e.g., *Disassembly Type ID, Disassembly Type Code,* and *Disassembly Type Name* (see **Figure 4-12**).

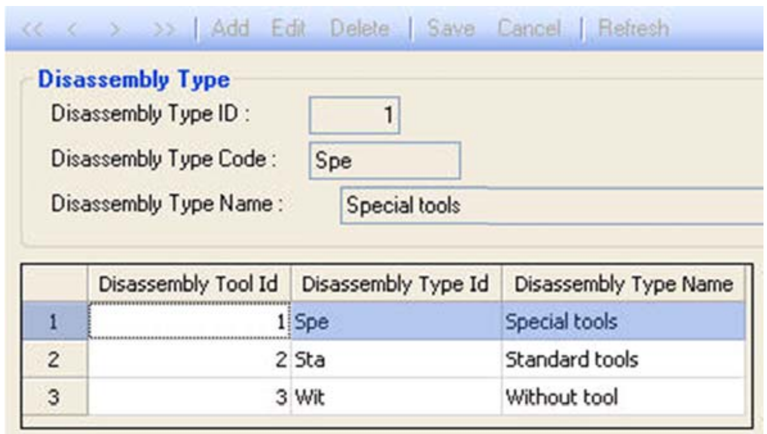


Figure 4-12: [Joint] – model > (Disassembly Type).

4.6.3 Disassembly Tool

The [Disassembly Tool], contains necessary information on disassembly tools e.g., *Disassembly Tool ID, Disassembly Type, Disassembly Tool Code,* and *Disassembly Tool Name* (see **Figure 4-13**).

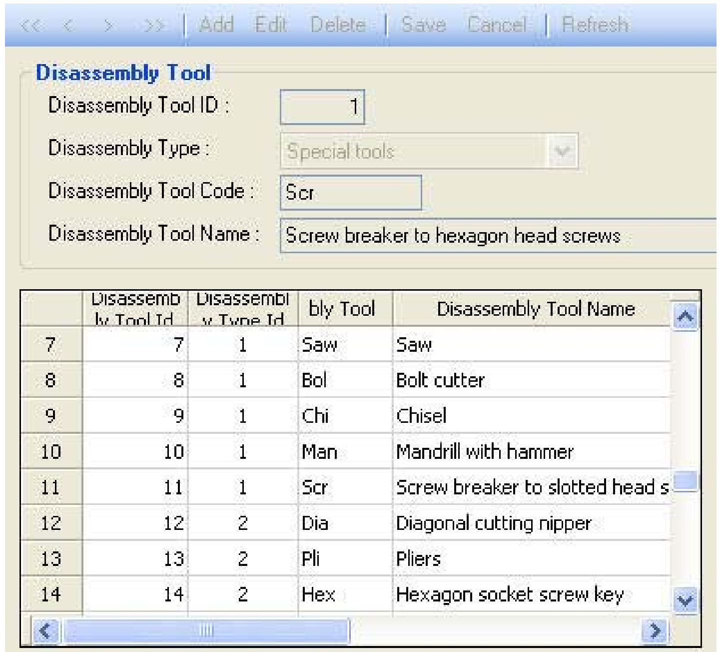
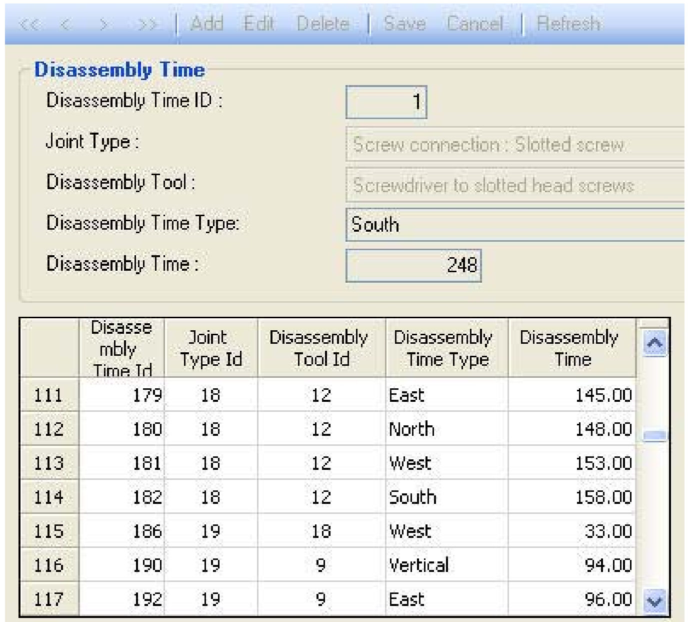


Figure 4-13: [Joint] – model > (Disassembly Tool).

4.6.4 Disassembly Time

The [Disassembly Time], contains necessary information on disassembly time e.g., *Disassembly Time ID, Joint Type, Disassembly Tool, Disassembly Time Type,* and *Disassembly Time* (see **Figure 4-14**).



	Disassembly Time Id	Joint Type Id	Disassembly Tool Id	Disassembly Time Type	Disassembly Time
111	179	18	12	East	145.00
112	180	18	12	North	148.00
113	181	18	12	West	153.00
114	182	18	12	South	158.00
115	186	19	18	West	33.00
116	190	19	9	Vertical	94.00
117	192	19	9	East	96.00

Figure 4-14: [Joint] – model > (Disassembly Time).

4.7 Profit Model

The [Profit] – model, contains necessary information on profits of items within the project; it consists of four menu elements: (1) [Recycling Profile], (2) [Recycling Profit], (3) [Disposal], and (4) [Reuse], which are described in the following sections (see **Figure 4-15**).

Figure 4-15: [Profit] – model.

4.7.1 Recycling Profile

The [Recycling Profile], contains necessary recycling profiles e.g., *Profile (Country), Fraction, Fraction Definition (Code, Date, Reference, and Description), Fraction Material (Material Name, Material Weight Min./Max.), Fraction Cost (Material Name, Recycle, Reuse, Disposal,* and *Reference)*. These information are useful for recyclers to calculate the recycling cost/benefit on different material fractions (see **Figure 4-16**).

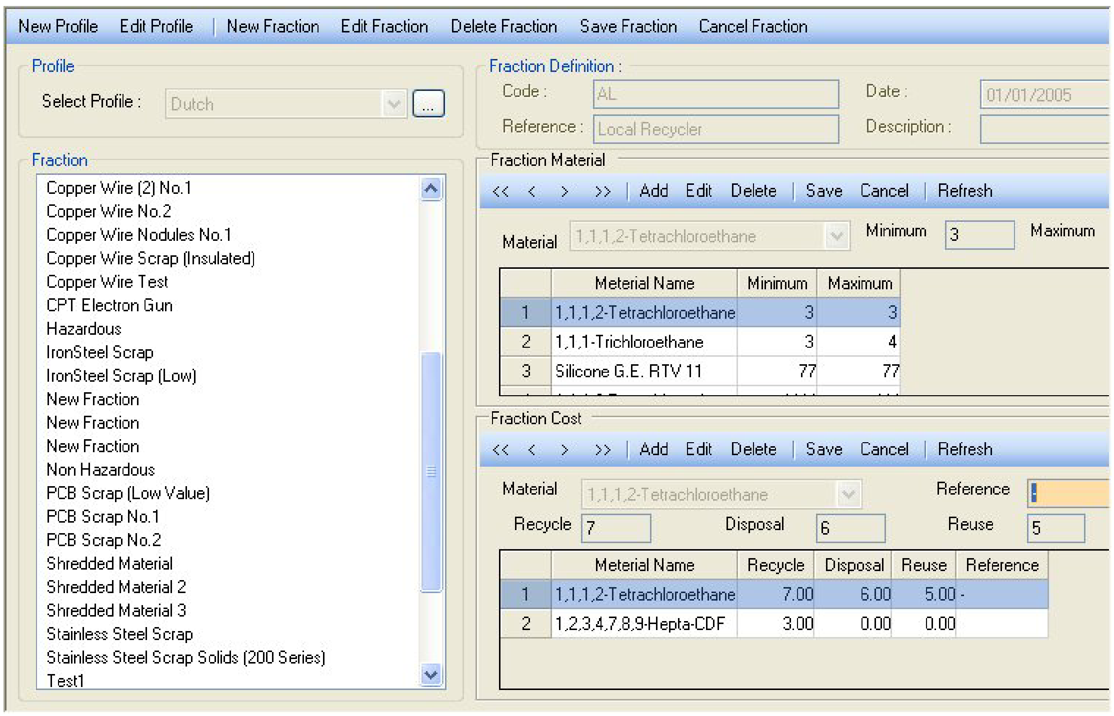


Figure 4-16: [Profit] – model > (Recycling Profile).

4.7.2 Recycling Profit

The [Recycling Profit], contains necessary information on recycling profits e.g., *Proceed Recycle ID, Material, Country,* and *Recycling Price* (see **Figure 4-17**).

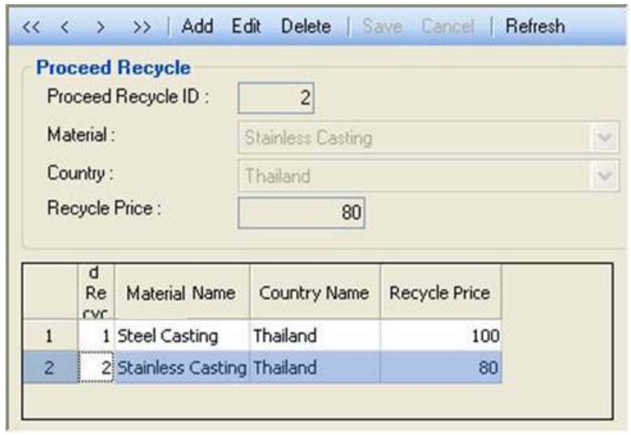


Figure 4-17: [Profit] – model > (Recycling Profit).

4.7.3 Disposal

The [Disposal], contains necessary information on disposal profiles e.g., *Disposal ID, Material, Country,* and *Disposal Price* (see **Figure 4-18**).

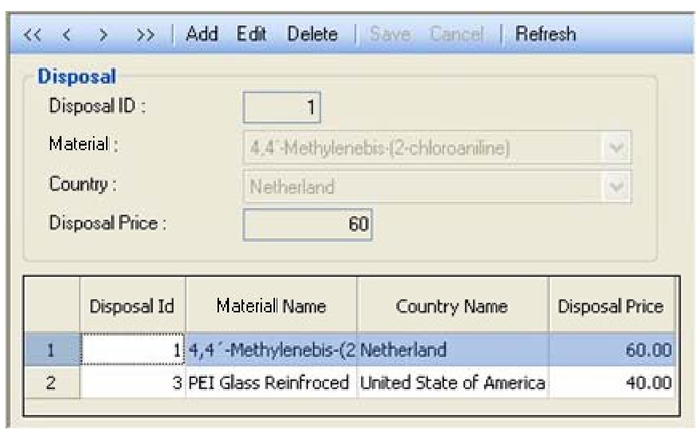


Figure 4-18: [Profit] – model > (Disposal).

4.7.4 Reuse

The [Reuse], contains necessary information on reuse profiles e.g., *Reuse ID, Material, Country,* and *Reuse Price* (see **Figure 4-19**).

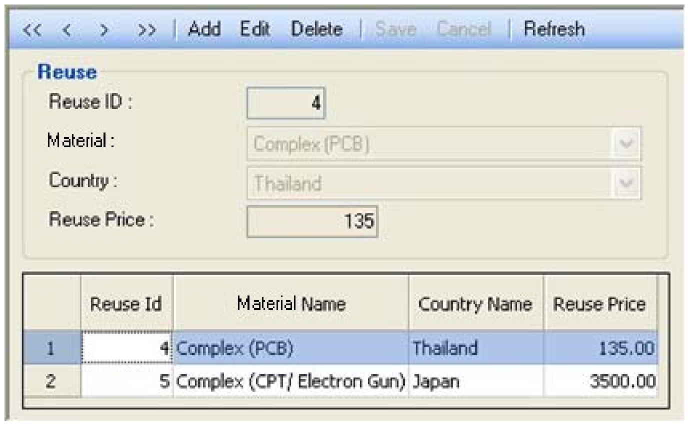


Figure 4-19: [Profit] – model > (Reuse).

4.8 Product Model

The [Product] – model, contains necessary information on product attributes which can be recalled within the project; it consists of seven menu elements: (1) [Products], (2) [Item of Product], (3) [Material of Item], (4) [Joint Type of Item], (5) [Disassembly Time of Item], (6) [Item Profit], and (7) [Product Performance Indicator] (see **Figure 4-20**).

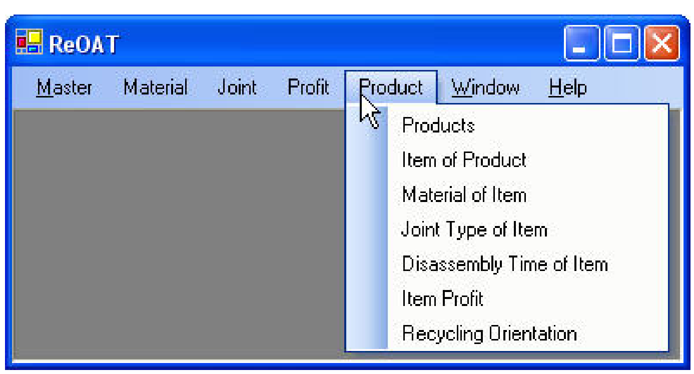


Figure 4-20: [Product] – model.

4.8.1 Products

The [Products], contains necessary information on product profiles e.g., *Product ID, Product Code, Product Name,* and *Product Value* (see **Figure 4-21**).

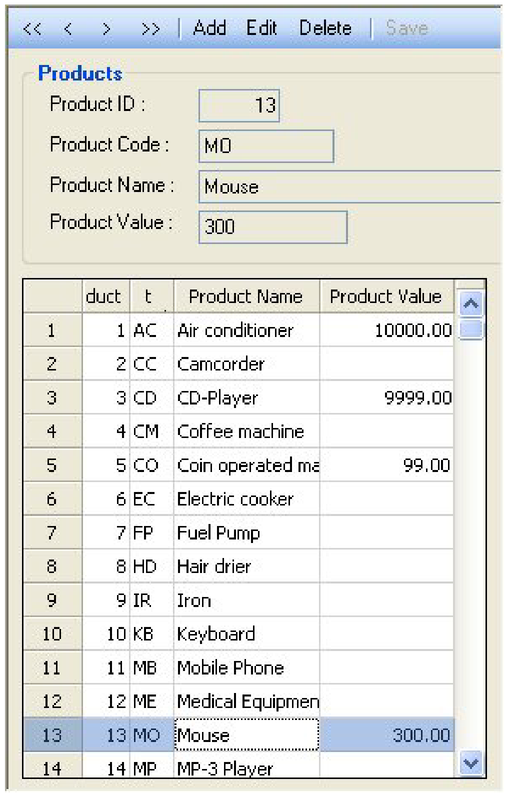


Figure 4-21: [Product] – model > (Products).

4.8.2 Item of Product

The [Item of Products], contains necessary information on items of product profiles e.g., *Product, Item of Product ID, Item of Product Code, Item of Product Name, Dimension, Shape, Weight,* and *Accessibility* (see **Figure 4-22**).

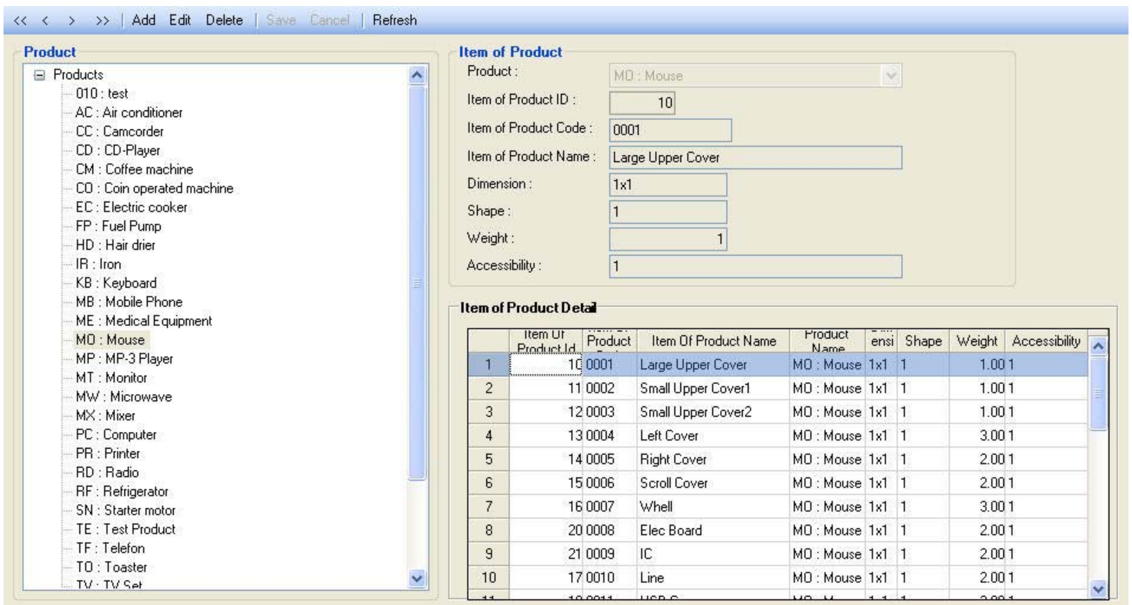


Figure 4-22: [Product] – model > (Item of Product).

4.8.3 Material of Item

The [Material of Item], contains necessary information on details of item profiles e.g., *Material of Item ID, Product, Item of Product,* and *Material* (see **Figure 4-23**).

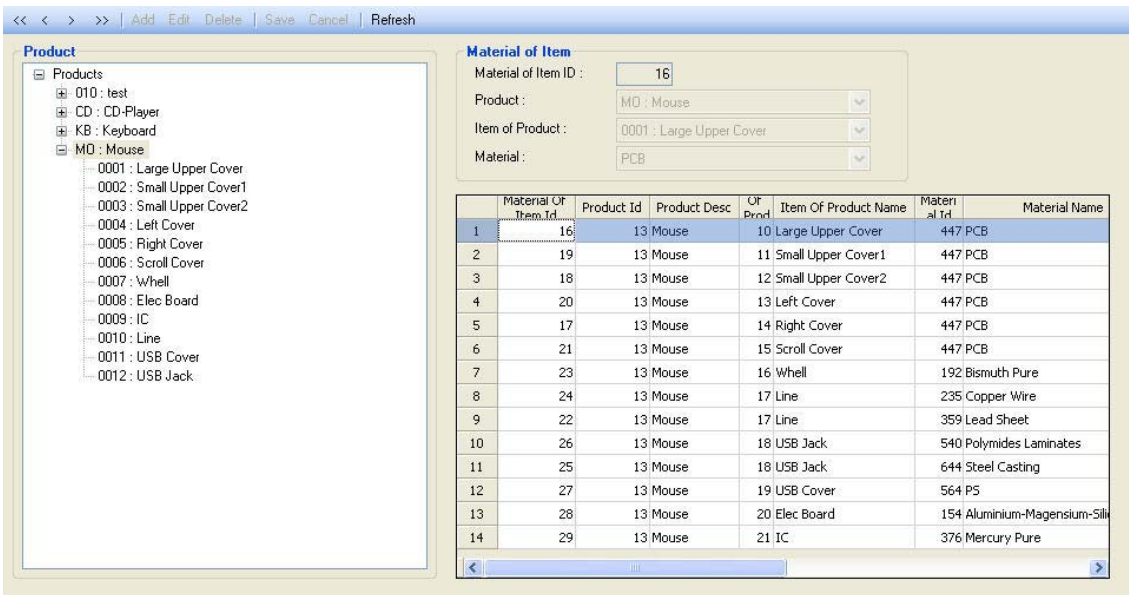


Figure 4-23: [Product] – model > (Material of Item).

4.8.4 Joint Type of Item

The [Joint Type of Item], contains necessary information on joint type of item profiles e.g., *Product, Item of Product, Item of Product2* and *Joint Technique* (see **Figure 4-24**).

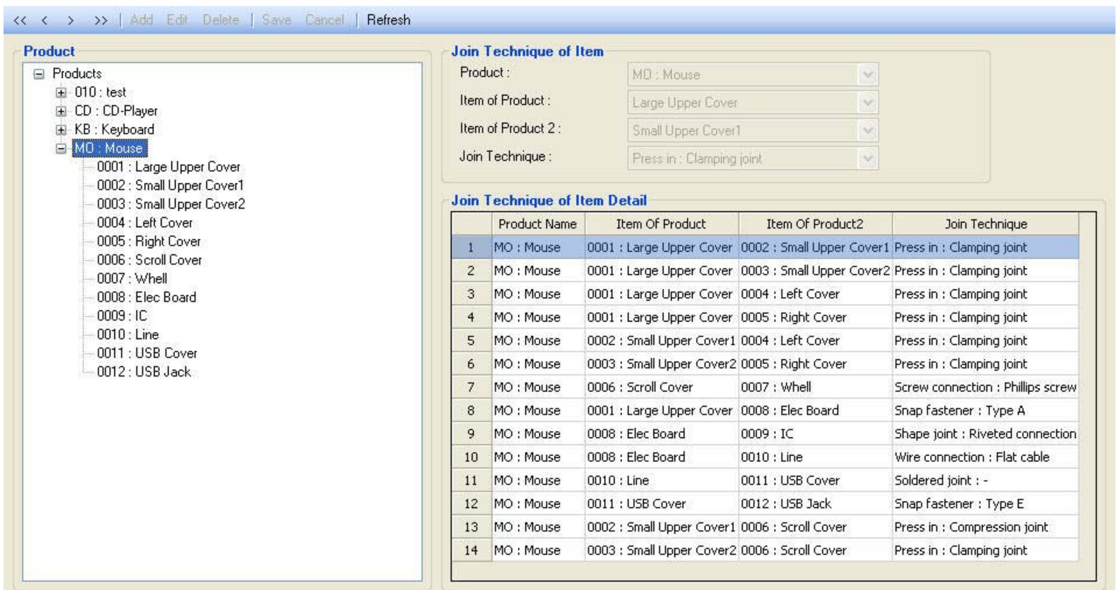


Figure 4-24: [Product] – model > (Joint Type of Item).

4.8.5 Disassembly Time of Item

The [Disassembly Time of Item], contains necessary information on the products disassembly profiles e.g., *Disassembly Time of Item ID, Join Technique of Item, Product, Item of Product, Join Technique, Disassembly Join Technique Time, Disassembly Time* and *Disassembly Time of Item Cost* (see **Figure 4-25**).

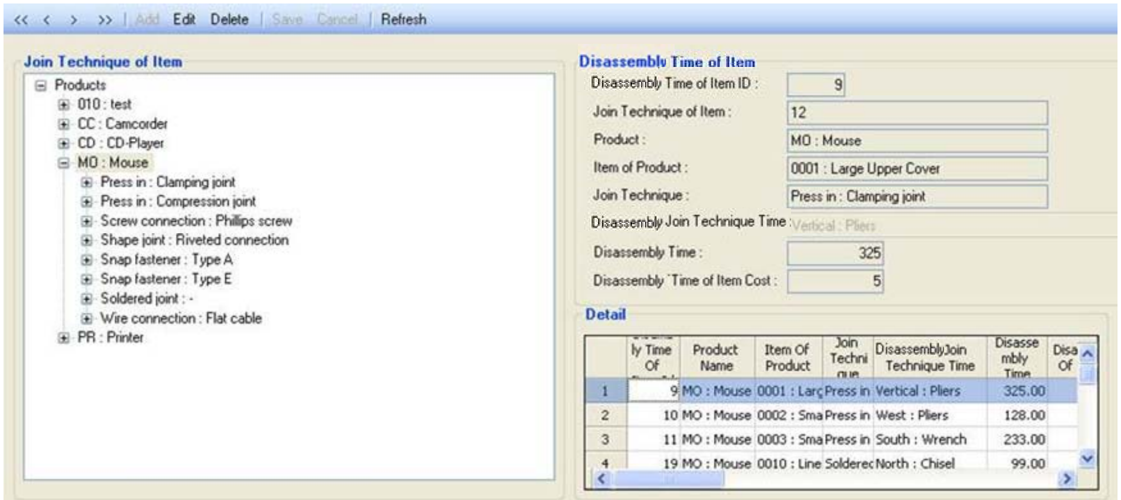


Figure 4-25: [Product] – model > (Disassembly Time of Item).

A number of tests on separating two parts that connect with various joint types had been carried out. The time spent for disassembling different joint types were recorded and used as the raw data for calculating the disassembly cost (see **Appendix, Table A-28**). When disassembling, every disassembled part has to be identified (mainly on their name, material, weight, connections, sequences, and quantity). The algorithm of how the parts are connected is called a "sequence." A "predecessor" is the part that has to be removed prior to reach the next part "successor" (see also **Section 5.4.2.8**). When all parts' sequences and connection types have been declared, the product structure can be built. These information also assist in discovering the optimal disassembly pathway.

4.8.6 Item of Profit

The [Item of Profit], contains necessary information of items of profit profiles e.g., *Product, Item, Material, Recycle, Disposal,* and *Reuse* (see **Figure 4-26**).

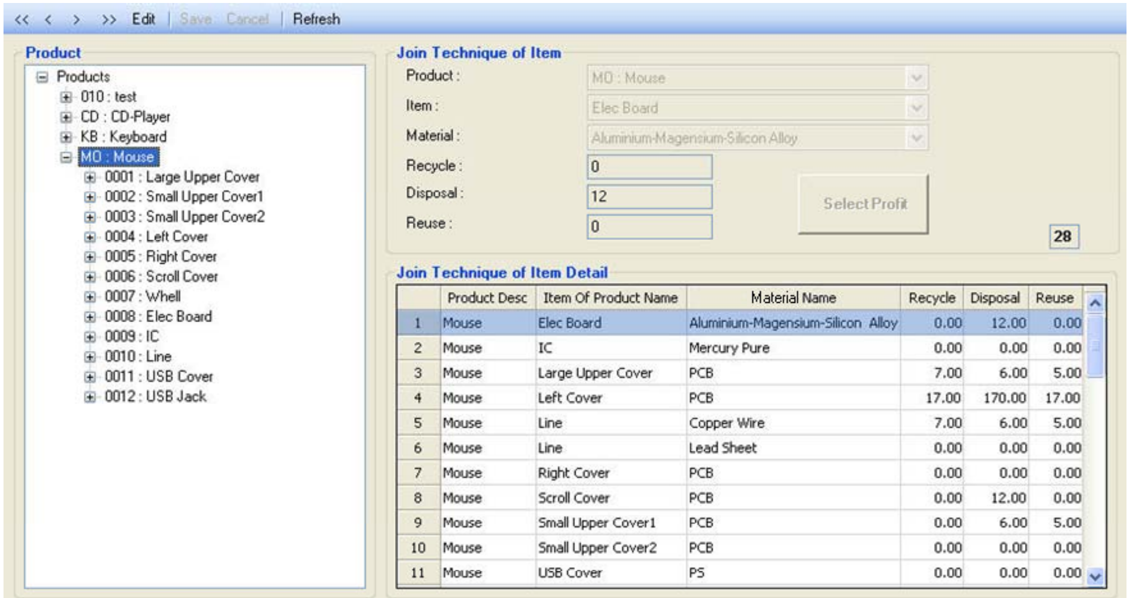


Figure 4-26: [Product] – model > (Item of Profit).

4.8.7 Recycling Orientation / Recycling-Oriented Product Design Category

Recycling rate of product alone is not sufficient to represent overall product recycling performance, therefore other relevant issues also need to be considered. Generally, in product design for assembly/disassembly/recycle, the attributions of each part of the product contribute to the product performance. At least twenty-two relevant issues (categories) influence product recycling performance: (1) Accessibility, (2) Ease of handling, (3) Cable connections, (4) Integration of cables, (5) Joint types, (6) Marking of hazardous materials, (7) Marking of plastics, (8) Material purity of parts, (9) Non-destructive connections, (10) Part compatibility of plastics, (11) Preferred joint type, (12) Preferred materials, (13) Priority of hazardous waste parts, (14) Priority of recyclable parts, (15) Quantity of joint elements, (16) Ratio of disposal, (17) Ratio of disposal as hazardous, (18) Total compatibility of plastics, (19) Use of recycled plastics, (20) Variety of joint types, (21) Variety of necessary tools, and (22) Variety of plastics (see **Figure 4-27**).

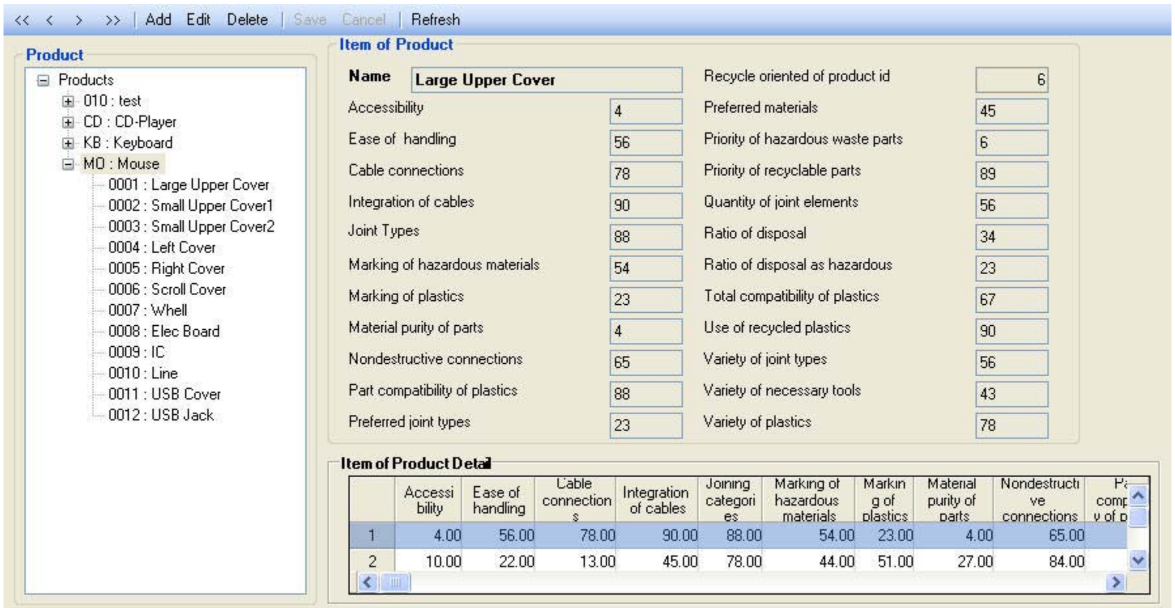
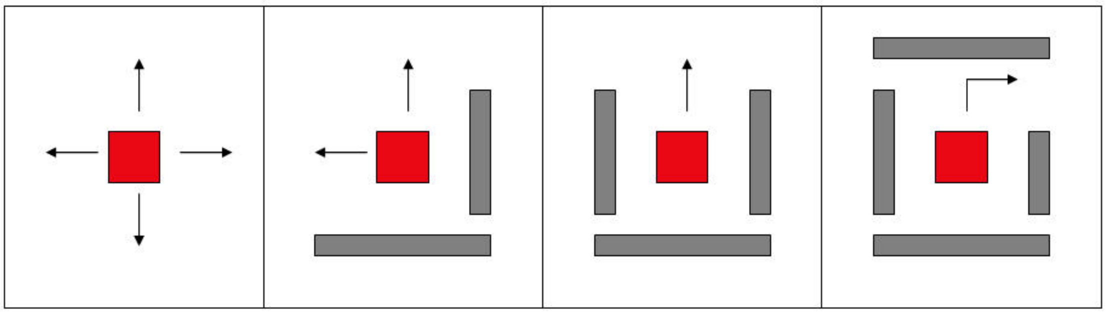


Figure 4-27: [Product] – model > (Product Orientation).

In order to determine the recycling-orientation of product at design stage, these twenty-two categories have to be assigned values by the users according to their descriptions/criteria, which will be recorded and further employed in the calculation stage. Each of the twenty-two categories description/criteria are described in the following sections. This list is catalogued in **Appendix**, (see **Table A-1**).

4.8.7.1 Accessibility

In product assembly/disassembly context, accessibility refers to the quality of reaching or accessing the target (part), by a degree of accessibility. Degree of accessibility refers to how easy to insert or remove a part. The degree of accessibility influences directly recycling performance when disassembling products. By means of ReOAT's data acquisition and interpretation, and to facilitate the calculation mechanism, the degree of accessibility has been converted and given specific score, the higher the accessibility score the higher the part's accessibility e.g., a part with 100 accessibility scores has *excellent* chance to be inserted or removed into/from the product. Users assign *Accessibility score* within the range of 1-100, according to the degree of accessibility of the product. The *Accessibility* (degree) is illustrated in **Figure 4-28**.



excellent *fair* *poor* *re-design*

Figure 4-28: Accessibility, *(top view)*.

Hint about *Accessibility score* is illustrated in **Appendix** (see **Table A-2**).

4.8.7.2 Cable Connections

The higher the number of cables between parts the higher the time required for manual assembly/disassembly. The determination of *Cable connection score* is described in **Appendix** (see **Table A-3**).

4.8.7.3 Ease of Handling

A product, which can be handled easily, facilitates recycling operations. Shape of products plays an important role and has influence on handability. A product with good handability is preferred in recycling operations (Boothroyd, 1994). Approach such as global shape descriptions as a "shape envelop," is used for rating the handability. The shape envelop is obtained by projecting the edges of the product to the coordinate planes (axes). General global features are such as: length, height, and width, (L x H x W), are used to determine handability. In ReOAT the global shape can be classified into six shape envelopes: (1) Box, (2) Flat rectangular, (3) Rectangular rod, (4) Cylinder, (5) Flat cylinder, and (6) Round rod (see **Figure 4-29**).

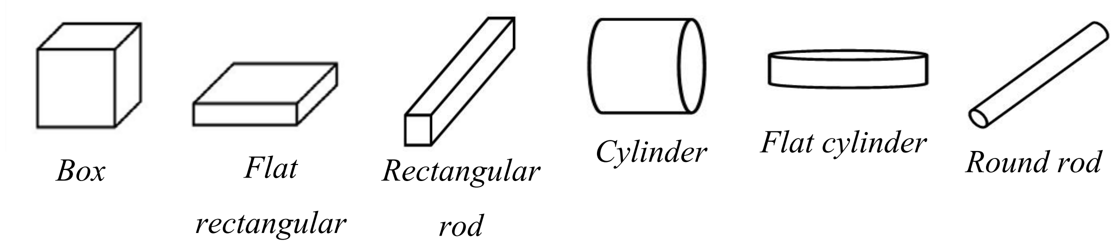


Figure 4-29: Shape envelop.

The users have to determine the shape envelop in which their products can be categorized. Specific score is given to each shape envelop. Users assign *Ease of handling score* within the range of 1-100 by the hint about scores given in **Appendix** (see **Table A-4**). The higher the degree of handability the higher the handability score *(Ease of handling score)* e.g., *Box* (shape envelop) has 100 score.

4.8.7.4 Integration of Cables

Generally, cables are used to transmit signals, or electricity, or both at the same time, most electrical and electronic equipments incorporated a number of cables into their specifications. Numbers of cables are usually assembled into one cable bundle (harness) to ease for manual assembly/disassembly, a completed harness assembly consists of a main trunk, where multiple wires or cables are bundled and tied together with individual wires or smaller bundles of wires leaving the main trunk at various points known as “breakouts” (Boothroyd, 1994). The cable terminal’s physical characteristics (breakouts), are classified into seven categories, in the integration of cables: (1) Assembled connector, (2) Quick connect terminal (lug), (3) Fork terminal (lug), (4) Terminal (lug), (5) Tinned wires, (6) Ring terminal (lug), and (7) Leg (outlet). The *Integration of cables* are diagrammtically illustrated in **Figure 4-30**.

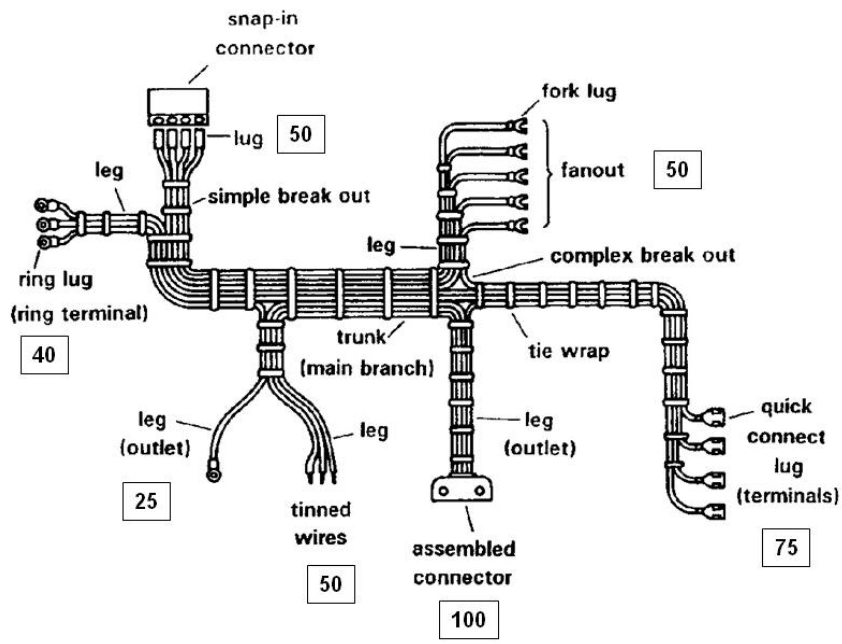


Figure 4-30: Integration of cables (source: Boothroyd, 1994).

Integration of cables have been cataloged and given a score according to their physical characteristics. The higher the number of cables between parts the higher the time required for manual assembly/disassembly the lower the score. The determination of *Integration of cables score* is illustrated (hint) in **Appendix** (see **Table A-5**).

4.8.7.5 Joint Types

Variety of joint types are designed according to their purposes/functions e.g., water tightness, permeability, gas tightness, electrical insulation, electrical conduction, heat insulation, heat conduction, stiffness, flexibility, corrosion resistance, vibration resistance, pressure resistance, damp resistance, temperature resistance, sliding, rotation, inspection, reliability in inaccessible places, and so on. It is preferred that the two parts are joint by using as small number of "joint elements" as possible, to reduce the disassembly time (see **Figure 4-31**).

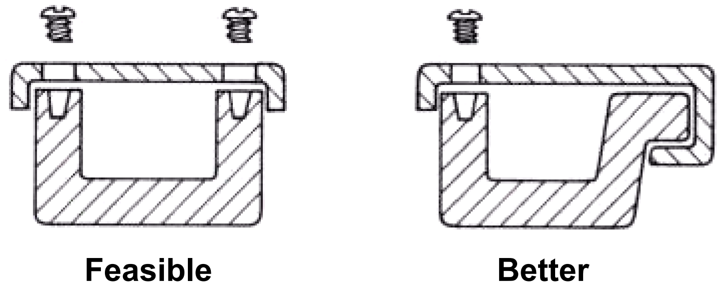


Figure 4-31: Joint types (joint elements) (source: Bralla, 1986).

The higher the number of "joint elements" between parts the higher the time required for manual assembly/disassembly, the higher the joint types score. Moreover, parts that are joining together should be compatible with each other, without unwanted effects on e.g., binding, slipping, chemical action, electrolytic action differential expansion due to temperature or damp, and other problems. A joint may need to be reliable for many years, easily demountable for inspection, modification, or repair. The determination of *Joint types score* is described in **Appendix** (see **Table A-6**)

4.8.7.6 Marking of Hazardous Materials

To facilitate recycling operations flame retardants, and other hazardous parts should be marked. The hazardous part, fraction needs to be separated to avoid mixing with other material fractions, prior to recycling. EU RoHS directive (Directive 2002/95/EC, 2003) recommends a reduced use of heavy metals and the Halogenated flame retardants (e.g., in plastics, circuit boards, foams, wire, insulation, and packaging). It restricts the use of mercury (e.g., in electrical, relays/switches, lamps, batteries, and packaging inks), cadmium (e.g., in thick film inks on circuit boards, batteries, and packaging inks), lead (e.g., in interconnect systems, weights, lubricants, glass, paints, coatings, and packaging inks), chromium VI (e.g., in thick film inks on circuit boards, metal platings, and packaging inks), and bans on PBB and PBDE (Nortel, 2000).

In ReOAT, a part which is marked with a hazardous symbol (easy-to-spot, and facilitate recycling) is assigned for 100 scores, a parts which has no mark is susceptible to escape notice and difficult to proved whether it is hazardous or not is assigned a score 0. The determination of *Marking of hazardous material score* is described in **Appendix** (see **Table A-7**).

4.8.7.7 Marking of Plastics

Figure 4-32 does not automatically mean that the plastic is recyclable, neither does number 5 indicates 5 times of recycled. It just an indication of the "family" of plastics it is made from. Number 5 within arrows means polypropylene or PP. Automobile battery cases, signal lights, battery cables, ice cream buckets, are often made from this (APC, 2004b).

Figure 4-32: Plastics type symbol (source: APC, 2004).

There are about 50 different groups of plastics, with hundreds of different varieties. All types of plastic are recyclable. The American Society of Plastics Industry developed a standard marking code to help consumers identify and sort the main types of plastic. Seven types of plastics have been categorized according to their recycling properties: (1) PET, (2) HDPE, (3) PVC, (4) LDPE, (5) PP, (6) PS, and (7) Other (see **Table B-3**). To facilitate recycling operations, plastics parts should be marked. Different plastics (fractions) need to be separated to avoid the mixing with other material fractions prior to recycling. A plastic weighting more than 25 g should be marked with its plastics type (symbol/letter) (ISO 11469, 2000). Plastics consumption is growing about 4% every year in western Europe. We produce and use 20 times more plastic today than we did 50 years ago (Waste Online, 2005).

Plastics contribute to sustainable development, it has been used to produce several goods ranging from foods containers, medical devices, household appliances, electronic devices; without plastics many lives could not be sustained. In **Appendix, Figure** B-2 diagrammatically illustrates how plastics has contributed to SD. Due to the resource limitation, use of recycled plastics helps to reduce the demand of virgin materials (crude oil). The marking of plastics facilitates the sorting process for recycling. The marked plastics gets 100 score. On the other hand, plastics part which has no mark is susceptible (no identity proved), thus score 0 is given to this unclear form. The determination of *Marking of plastics score* is described in **Appendix** (see **Table A-8**).

4.8.7.8 Material Purity of Parts

Ultimately, in product design to facilitate recycling operations, a product should be designed based on a single type of material, or materials that are compatible, otherwise it should be designed in such a way to ease disassembly/recycling. This issue is currently the main concern in design department in most large industries. In ReOAT, a part is defined as the smallest disassembly unit. When a part is made from a single material a score of 100 is given. In contrast, when more than one material are used, a score of 0 is given. The determination of *Material purity of parts score* is described in **Appendix** (see **Table A-9**).

4.8.7.9 Non-destructive Connections

A destructive connection prevents the "reuse" of the part, and results in high disassembling time. In recycling-oriented product development, this kind of joint type should be avoided, or in other words *Non-destructive connections* is preferred (VDI 2243, 2002). **Figure 4-33** illustrates types of destructive connections e.g., welding.

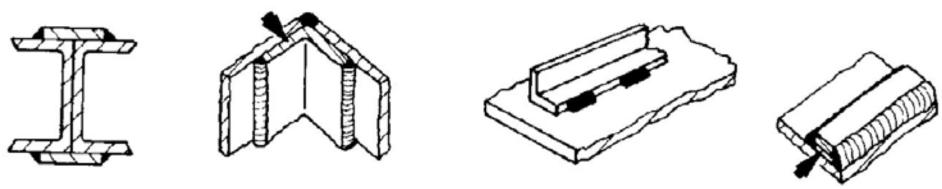


Figure 4-33: Destructive connections should be avoided (source: Bralla, 1986).

The determination of *Non-destructive connections score* is described in **Appendix** (see **Table A-10**).

4.8.7.10 Part Compatibility of Plastics

To facilitate recycling operations, plastics parts in the product should be compatible with each other. Incompatible plastics parts prevent the recycling process at high quality. 80% of plastics produced today is made from thermoplastic. The product designers should design product comprises parts which are compatible. The *Thermoplastics compatibility table* is shown in **Table A-24.** From this table, thermoplastics are classified into three degree of compatibility e.g., (1) compatibility, (2) compatibility in some case (usually blend), and (3) non-compatible. With the help of this table, designers can improve the product recycling performance by selecting plastics that are compatible with each other. For example, the product comprises of two plastic parts. If Part-1 is made from Polycarbonate, and Part-2 should consider a compatible material (with Part-1) e.g., ABS (most compatible with Polycarbonate), Acrylic, Noryl, Polytherimide, or Polysulfone (blendable). In ReOAT, the higher the degree of compatibility of plastics the higher the Part compatibility of plastics score. The determination of *Part compatibility of plastics score* is described in **Appendix** (see **Table A-11**).

4.8.7.11 Preferred Joint Types

Disassembly of products, is largely depended on the joint types used. Joint types that are robust for connecting parts at the same time easy to disassembling are preferred. The higher the difficulty of disassembling parts the higher the time required for manual assembly/disassembly. For example, snap fastener is more preferred to welding. **Figure 4-34** diagrammatically illustrates choices of joint types. The degree of separability between parts is ascertained from the experimental disassembly time required to disconnect each joint type (see **Appendix, Table A-25**).

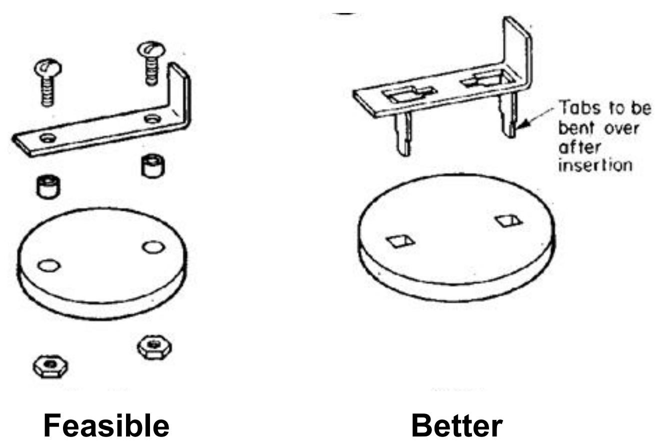


Figure 4-34: Preferred joint types (source: Bralla, 1986).

In ReOAT, the score of preferred joint types depends on the degree of separability between parts. The higher the degree of separability between parts the higher the *Preferred Joint Types score*. The determination of *Preferred Joint Types score* is described in **Appendix** (see **Table A-12**).

4.8.7.12 Preferred Materials

Each material has different recyclability rate e.g., (1) excellent recyclability, (2) good recyclability, (3) poor recyclability, and (4) bad recyclability. A degree of recyclability of each material is given e.g., (1) metals has *excellent* recyclability (degree 3; (2) plastics has *fair* recyclability (degree 2); (3) concrete and banned materials have *poor* recyclability (degree 1; and (4) rubber and hazardous materials have *bad* recyclability (re-design) (degree 0) (see also **Appendix, Table A-13**). In order to obtain high recycling rates, materials which are favourable to recycling process at their EOL should be used. The preference of material can be determined from its recyclability property (e.g., *excellent, fair, poor, and bad*). The higher the degree of recyclability, the higher the preferred material score. For instance, material which has the highest degree of recyclability (*excellent*) will have the highest *Preferred material score*, i.e., 100.

4.8.7.13 Priority of Hazardous Waste Parts

A part which is needs to be disposed of or requires a special treatment, due to the existence of hazardous substances, should be placed at a position where it can be taken off easily, or it should have as little dismantling obstacles as possible. The *Priority of hazardous waste parts* is illustrated in **Figure 4-35**.

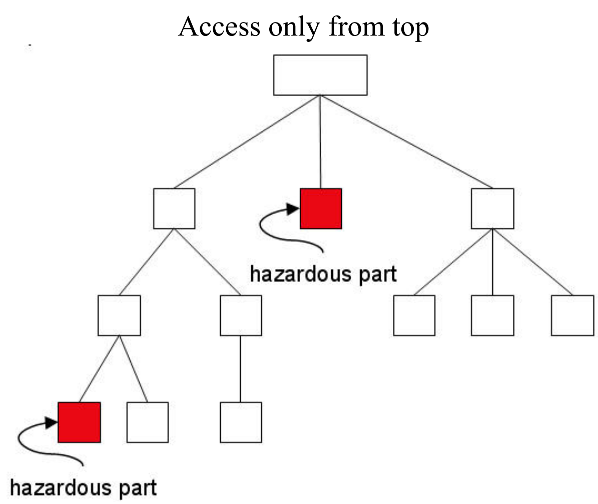


Figure 4-35: Priority of hazardous waste parts.

A comparison of different number of items to be removed before reaching hazardous/waste part is shown in the figure above. A hazardous/waste part located in the middle of the figure is easier to reach than a hazardous/waste located in the left corner of the figure, because there are fewer items to be removed before reaching the hazardous/waste part. The fewer the number of parts that have to be removed before reaching the hazardous/waste part, the higher the *Priority of hazardous waste score*. The determination of *Priority of hazardous waste score* is described in **Appendix** (see **Table A-14**).

4.8.7.14 Priority of Recyclable Parts

A part which is "recyclable" due to the substances recycling properties should be placed at a position where it can be taken off easily, or where there are little dismantling obstacles as possible. The *Priority of recyclable parts* is illustrated in **Figure 4-36**.

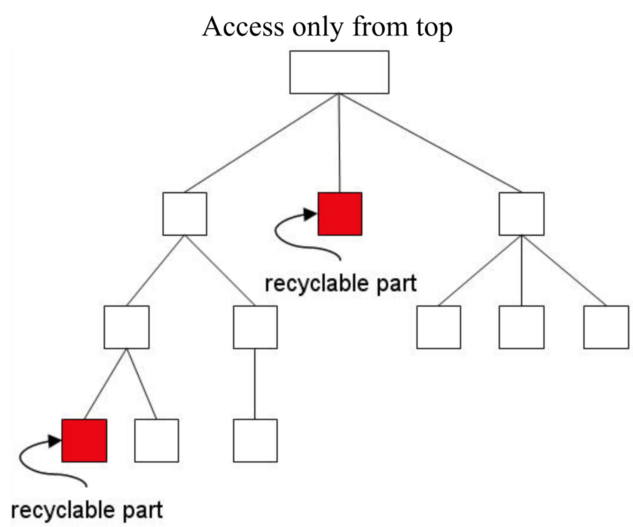


Figure 4-36: Priority of recyclable parts.

A comparison of different number of items to be removed before reaching the recyclable/valuable part is shown in the figure above. A recyclable part located in the middle of the figure is easier to reach than a recyclable part located in the left corner of the figure, because there are fewer items to be removed before reaching the recyclable/valuable part. The fewer the number of parts that have to be removed before reaching the recyclable/valuable part the higher the *Priority of recyclable score*. The determination of *Priority of recyclable score* is described in **Appendix** (see **Table A-15**).

4.8.7.15 Quantity of Joint Elements

The shorter the disassembly time of each connection the more feasible the recycling operations and the cheaper the disassembling cost (personal wage/hour). In order to reduce the disassemble time, the number joint elements have to be as small as possible. A comparison of number of items to be removed before reaching the target part is illustrated in **Figure 4-37**.

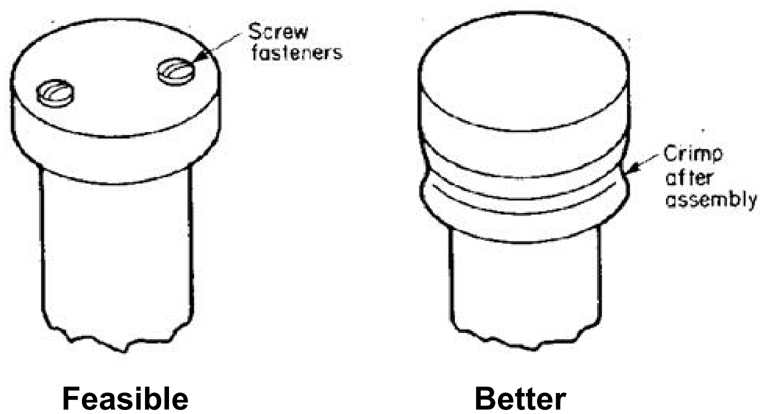


Figure 4-37: Quantity of joint elements (source: Bralla, 1986).

In the figure, the item (left) has two screw fasteners that have to be removed before the two parts can be separated. Assuming that the time needed to remove each (single) joint element is the same e.g., the time needed to remove one screw fastener is equal to the time needed to remove a crimp. The item (right) that has one joint element is preferred. The fewer the quantity of joint element that have to be removed before reaching the target part the higher the *Quantity of joint elements score*. The determination of *Quantity of joint elements score* is described in **Appendix** (see **Table A-16**).

4.8.7.16 Ratio of Disposal

In order to increase the share of recycling and the reuse of parts, recyclable materials and reusable parts should be used as much as possible. To avoid waste generation, the ratio of disposable has to be as smallest as possible; this is in line with waste minimization concept i.e., 3R: reduce, reuse, and recycle (see **Section 2.2**). **Figure 4-38** diagrammatically illustrates a condition of collected materials. One-fifth of its compositions (by weight) is a disposable part (i.e., disposable 25%, or the ratio of disposal part is equal to 0.25).

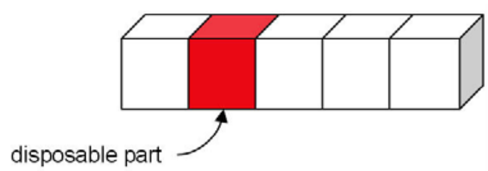


Figure 4-38: Ratio of disposable part (by weight).

A *Ratio of disposable* 0.00-0.25 is *excellent* [i.e., in line with WEEE (Directive 2002/96/EC, 2003), sets 65% for recycling quotas (rate) for IT and telecommunications equipment and this should be meet by December 2006 (the ratio of disposal should be at most 35%), (see also **Appendix B.1**)].The higher the recycling rate the higher the *Ratio of disposal score*. A *Ratio of disposal score* of 100 is *excellent.* The determination of *Ratio of disposal score* is described in **Appendix** (see **Table A-17**). In addition to this, processes for material recycling and markets for reusable parts have to be established (i.e., concept of industrial ecology, see **Section 2.3**).

4.8.7.17 Ratio of Disposal as Hazardous

In order to minimize environmental impacts, the production, use, and disposal of hazardous materials should be avoided. As LCA & IPP concepts are focusing on minimization of environmental impacts during the entire life of products by using the life-cycle thinking concept), to avoid hazardous waste disposal the ratio of disposal as hazardous has to be as small as possible. A *Ratio of disposable as hazardous* 0.00 is *excellent* [i.e., in line with RoHS (Directive 2002/95/EC, 2003) that prohibit the use of certain hazardous materials, within the life-cycle of product]. **Figure 4-39** diagrammatically illustrates a condition of collected materials e.g., one-fifth of its compositions (by weight) is disposable as hazardous part (i.e., disposable as hazardous 25%, or the ratio of disposal as hazardous part is equal to 0.25).

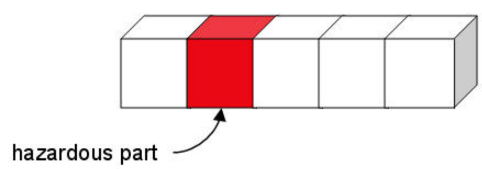


Figure 4-39: Ratio of disposal as hazardous part (by weight).

The higher the recycling rate the higher the *Ratio of disposable of hazardous score*. A *Ratio of disposable of hazard score* of 100 is *excellent* (see **Appendix, Table A-18**). In addition to this, processes for material and hazardous waste recycling and hazardous waste treatment have to be established (i.e., concepts of cleaner technology, and industrial ecology should be applied, see **Section 2.1** (page 18), and **Section 2.3**, respectively).

4.8.7.18 Total Compatibility of Plastics

In product design, the compatibility of materials between parts are important for products that comprise several parts which are in contact with chemical substances e.g., dilutions, solvents. To serve products functionalities some specific issues need to be assured: (1) to ascertain products safety (e.g., parts capability of performing at elevated temperatures, non-flammable, non-conductive, and non-corrosive); and (2) other industrial specific design considerations (e.g., electrical design, and optical design).

Designers should balance the materials used in products and their key properties e.g., in designing the automotive fuel pump, the designer needs to ascertain that all parts that are in contact with oil do not have a chemical reaction with oil (compatible with oil). These compatibility considerations are beyond the scope of this dissertation. In order to handle issues of compatibility apart from plastics, designers should consult the expertise of other material sources.

The focus issues within the scope of this dissertation is the recycling-oriented product design. Due to the fact that a variety of plastics are used in a variety of products which often obstruct recycling operations e.g., sorting; recycling of plastics at EOL of products is considered most important. **Figure 4-40** illustrates an exploded-view of car components (toy) basically made from three types of plastics that are compatible (e.g., ABS, PS, and SAN) and can be recycled together.

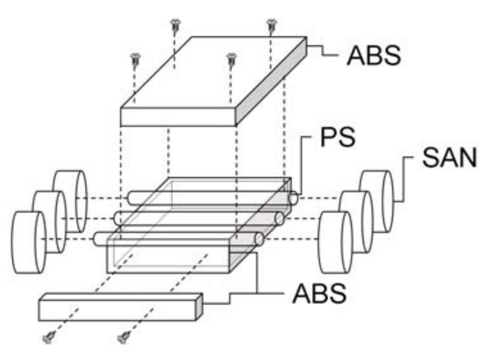


Figure 4-40: Total compatibility of plastics.

To ease the recycling process and reduce sorting of plastics parts, all plastics used within the product should be compatible with each other; compatible plastics can be easily sorted out and recycled together at their EOL. Total compatibility of plastics is derived from the average scores of individual plastic (part) compatibility. The determination of *Total compatibility of plastics score* is described in **Appendix** (see **Table A-19**).

4.8.7.19 Use of Recycled Plastics

The use of plastics in variety of applications continues to grow in volume and importance as design engineers, manufacturers, and consumers rely on the unique performance, low cost, and styling life-cycle benefits of plastics. The market for plastics goods increases each year, as the raw material i.e., crude oil is a finite resource representing stored solar energy, is expected to be depleted soon (see **Appendix B.5**). The absolute quantity of goods reaching their EOL is also increasing. There have led to increased attention on EOL management, loop-closing of materials by repair and reuse, for material and energy recovery. Closing the loops can be done in several ways e.g., increasing the use of recycled plastics in products [e.g., use 100 % recycled PC-ABS plastic in IBM desktop computer, and use 100% recycled PP plastic for automotive battery housing (APC, 2004a)].

By taking the minimization of the use of raw materials into consideration at the design stage, the new products can integrate the use of virgin and recycled materials. The more recycled plastics used in products, the higher virgin materials and resources are conserved. **Figure 4-41** diagrammatically illustrates plastics use in a product. The higher the ratio of recycled plastics used, the more preferred. In this sense, the ratio of recycled plastics used should be increased as much as possible up to 100% (by weight).

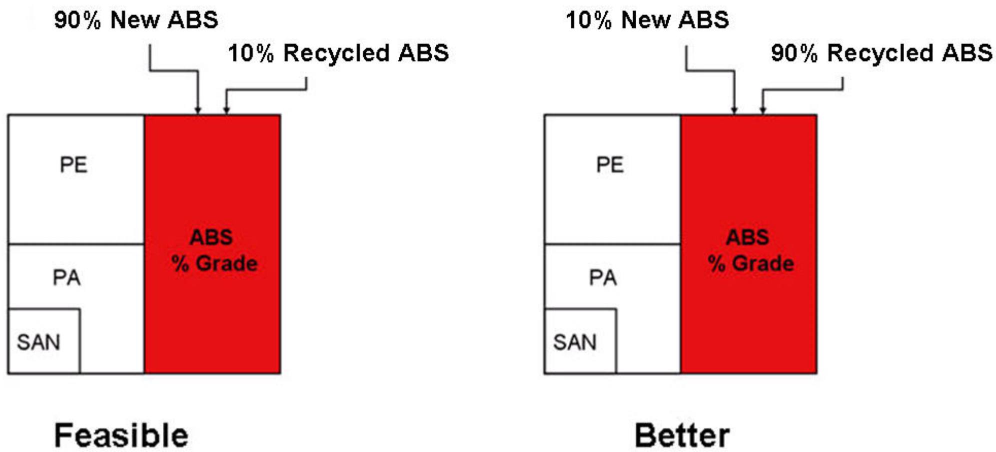


Figure 4-41: Use of recycled plastics (e.g., % recycled ABS, by weight).

The higher the *Ratio of recycle plastics used,* the higher the *Ratio of recycle plastics used score,* and the higher the reduction of virgin material and resources consumption (see **Appendix, Table A-20**). A *Ratio of recycle plastics used* in the products = 1.0 is *excellent*.

4.8.7.20 Variety of Joint Types

There are 14 common joint types in product design, which are recognized by ReOAT e.g., (1) Distort, (2) Embody/contact, (3) Extrusion coat, (4) Glued joint, (5) Hang up, (6) Press in, (7) Screw connection, (8) Shape joint, (9) Sliding joint, (10) Snap fastener, (11) Soldered joint, (12) Twisted up, (13) Welding, and (14) Wire connection (listed in **Appendix, Table A-26**). The fewer the *Variety of joint types,* the more feasible the disassembly of product (see **Figure 4-42**).

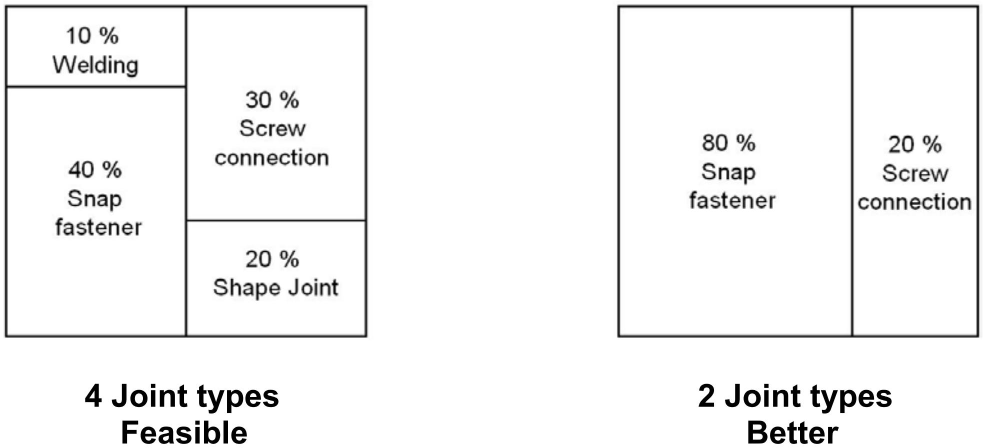


Figure 4-42: Variety of joint types.

In the figure, at the EOL of the product during manual disassembly, the product that has four joint types will take more time to disassembling than the product that has just two joint types. Thus, the product, which has two joint types, is more preferred than the product, which has four joint types. Ultimately, one feasible joint type is most preferred. The determination of *Variety of joint types score* is described in **Appendix** (see **Table A-21**).

4.8.7.21 Variety of Necessary Tools

There are 18 common tools use in dismantling process, which are recognized by ReOAT, e.g., (1) Bolt cutter, (2) Chisel, (3) Chisel with hammer, (4) Diagonal cutting nipper, (5) Hexagon socket screw key, (6) Mandrill with hammer, (7) Pliers, (8) Saw, (9) Screw breaker to cross-recessed head screws, (10) Screw breaker against hexagon head screws, (11) Screw breaker against hexagon socket screws, (12) Screw breaker against slotted head screws, (13) Screwdriver against cross-recessed head screws, (14) Screwdriver against slotted head screws, (15) Shell bit, (16) Soldering copper, (17) Tooless, and (18) Wrench. These *Variety of necessary tools* are listed in **Appendix, Table A-27**.

In disassembly process, the fewer the *Variety of necessary tools* used for disassembling the product the more feasible the recycling operations. The more the *Variety of necessary* *tools* used, the more time required for (preparing and changing) them. The determination of *Variety of necessary tools score* is described in **Appendix** (see **Table A-22**).

4.8.7.22 Variety of Plastics

The market for durable goods (e.g., automobiles, appliances, computers, and building and construction products) increases each year follows by the increasing number of recycling businesses. The driver for much of the durable goods recycling has been metals recovery, including ferrous, non-ferrous, and precious metals. However, interest in the recovery of plastics from EOL durable streams is also increasing, because plastics take an increasingly important role in the manufacture of durable goods.

Hundreds of types of plastics are produced and blended for variety of goods. Since the efficiency of plastics sorting processes (high precision) is not as high as those for metals, the quality of sorted materials depends on the material purity of parts. Unsorted plastics (mixed), when recycled together will degrade the quality of recycled plastics enormously.

For manual disassembly, in searching for reuse/valuable parts, e.g., in household appliances: it is difficult to sort plastics, because usually not every plastics part is marked, because of the economic importance, some plastics have tiny value (negligible) in the market therefore, they are not marked. In some case even though they are marked, but the marked is not always, guarantee its accuracy, often the markings are wrong (found later by plastic identification, test & analysis from laboratory). Therefore, to avoid the difficulty of sorting of plastics, the product should be designed to use appropriate types and numbers of plastics. Due to this fact, as few types of plastics as possible (see **Figure 4-43**).

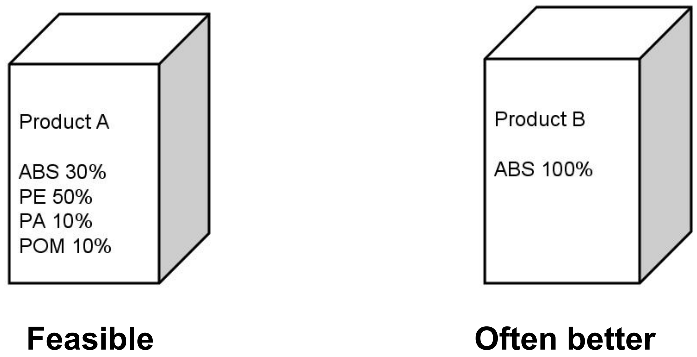


Figure 4-43: Variety of plastics.

The fewer the variety of plastics used in product the more feasible the production and the EOL management. The determination of *Variety of plastics score* is described in **Appendix** (see **Table A-23**).

4.8.8 Product Profit

The [Product Profit], provides necessary information on product profit profiles e.g., *Item Name, Weight, Disassembly Time, Disassembly Cost, Recycling Profit, and End-of-Life Cost* (see **Figure 4-44**).

Figure 4-44: [Product] – model > (Product profit).

4.9 Window Model

The [Window] – model, accommodates all opened ReOAT's screens. Navigation through the [Window] – model, by clicking [Window] – model > (custom select screen) revokes the selected screen(s) (see **Figure 4-45**).

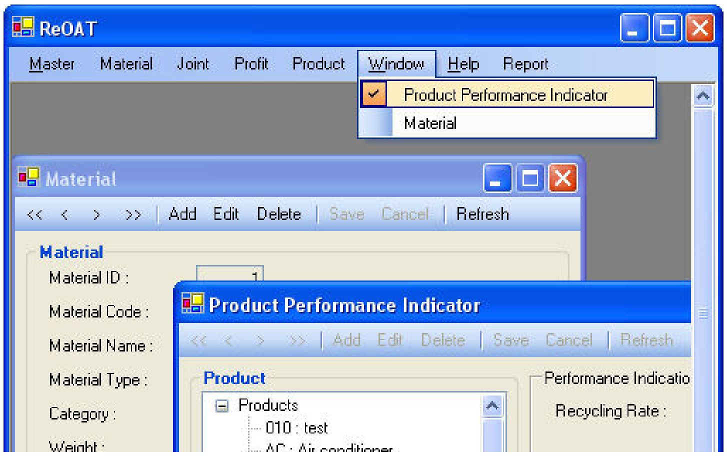


Figure 4-45: [Window] – model.

4.10 Help Model

The [Help] – model, provides necessary information on ReOAT *Troubleshooting*, which will be incorporated into the software in the future by collecting information and feedbacks from users at www.reoat.bravehost.com (see **Figure 4-46**).

Figure 4-46: [Help] – model.

4.11 Report Model

Users can use ReOAT for making products inventory, rating recycling-orientation of product design, and documenting reports. After inputting product profiles and necessary information into ReOAT, the product model can be built, modified, and finally generated reports as outputs. In ReOAT, four report categories are available e.g., (1) [Report Complete Disassembly], (2) [Report Optimal Disassembly], (3) [Report Product Orientation], and (4) [Report Performance Indicator] (see **Figure 4-47**).

Figure 4-47: [Report] – model.

In these four categories, there are six different printable reports. The six different printable reports are (1) Complete Disassembly Report, (2) Complete Disassembly Graph, (3) Optimal Disassembly Report, (4) Optimal Disassembly Graph, (5) Product Recycling Orientation, and (6) Product Performance Indicator (see **Figure 4-48**).

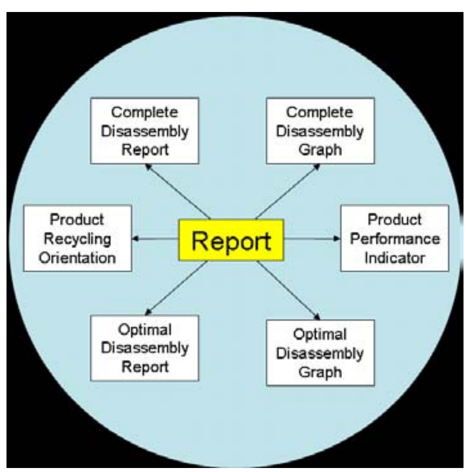


Figure 4-48: [Report] – model.

The six reports can be directly printed by click at [Report] – model, then select a desired report/graph, and printing (connected with printer)

4.11.1 Report Complete Disassembly (Report/Graph)

The [Report Complete Disassembly] > (Report/Graph), displays four relevant costs of products: (1) Disassembly Cost, (2) Disposal Cost, (3) Recycling Profit, and (4) End-of-life Cost.

4.11.2 Report Optimal Disassembly (Report/Graph)

The [Report Optimal Disassembly] > (Report/Graph), displays the optimal disassembly pathway, by optimizing disassembly cost, disposal cost, and recycling profit of every part of the product. The [Report Optimal Disassembly] > (Report) contains necessary information of product disassembly profiles e.g., Product, Item of Products, Item of Product 2, Join Technique, Join Technique of Item Detail, Item of Profit, Item of Product Name, Weight, Disassembly Time, Disassembly Cost, Disposal Cost, Recycling Profit, and End-of-Life Cost.

4.11.3 Report Product Orientation

The [Report Product Orientation], illustrates the recycling-orientation of product design (twenty-two categories, refer to **Table A-25, Appendix**).

4.11.4 Report Performance Indicator (PI/RI)

The [Report Performance Indicator], depicts the product quality. The higher the score of performance indicator the better the value of product will be. The report performance indicator considers mainly three issues:

1. *Recycling Rate (RR)*. RR is derived from a ratio of the recyclable materials and the total materials of the product (by weight)
2. *Recycling Orientation (RO)*. RO is derived from an average value of the twenty-two recycling-oriented product design categories
3. *Recycling Value (RV)*. RV is derived from a ratio of the product's EOL value and the initial price of the product (selling/purchasing price)

The indicator has been classified into two sub-indicators, based on different concerns: (1) *Performance Indicator (PI)*, and (2) *Recycling Indicator (RI)*; which are explained in the following sections.

4.11.4.1 Performance Indicator (PI)

Performance Indicator (PI), takes Recycling Rate (RR), and Recycling Orientation (RO) into account, regardless of the Recycling Value (RV). This indicator is a display of the geometric square root of RR, and RO. A number of legislations use the product's RR to regulate the materials compositions of products at their EOL. With rising demand of reused parts, recycled-materials, and product design for optimization; the EOL benefits are not only considered from the perspective of products with high RR, but also from products with high RO. The products with high RO ease and facilitate dismantling processes, and allow more retrieval of potential reusable parts/materials.

Global players usually set their product goals not only to maximize benefits but also to conform to legislations (RR) and favor EOL management (RO). Therefore, there should be a medium that equally shares the importance of RR and RO, and intrinsically expressed as an absolute value for displaying both performances simultaneously. Hence, the following equation is applied for these phases:

$$\text{Performance Indicator} = [\text{Recycling Rate x Recycling Orientation}]^{1/2}$$

$$\text{PI} = [\text{RR x RO}]^{1/2} \qquad \leftarrow(\textbf{Equation 1})$$

where PI = Performance Indicator; RR = Recycling Rate; RO = Recycling Orientation; and RR, RO ≥ 0.

After RR and RO are obtained, a so-called "Product Performance Indicator" can be plotted in a PI graph (2-D) as the intersection point of the projection of RO value from the x-axis and RR value from the y-axis. The PI graph has four equally divided region areas (square) namely: (1) Snails, (2) Monkeys, (3) Tigers, and (4) Eagles; by this way the absolute position is marked in one of the four areas. Each region (category) has its own description:

1. **Snails**. Snails are products with low score in both recycling orientation and recycling rate. To improve the product (recycling) performance, review of product design is essential.

2. **Monkeys**. Monkeys are products, which have improved recycling orientation but still have low recycling rate. These products present challenge for future development. The recycling rate can be improved by selecting proper materials (e.g. refer to materials, which have excellent recycling rate, cheap, and environmental friendly) or when new material & production technologies are available. The product with a high share of plastic materials evidently represents this case [used plastics (mixed) have low cost, not economical for recycling].

3. **Tigers**. Tigers are products that in spite of their low recycling orientation have a high recycling rate. These products have more than 50% of recycling rate and fulfil (many) company environmental objectives of having at least 50% recycling rate.

4. **Eagles**. Eagles are products, for which RR, and RO are more than 50%. They represent the state-of-the-art and set the standards of "green" products. This class of products integrates concepts of design for disassembly, design for environment, recycling technologies, take back, and recycling markets.

PI can be plotted on a 2-D graph, which comprises x-axis, and y-axis (see **Figure 4-49**).

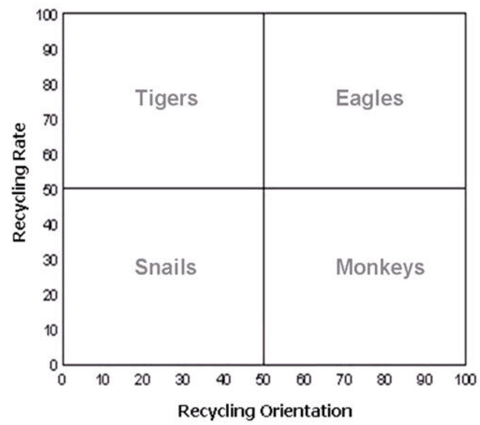


Figure 4-49: Performance Indicator (PI), 2-D.

Note. Various EU Directives have set the recycling rate (RR) of most products between 65-85% with particular deadlines, these targeted goals depend upon individual product category (see also **Appendix, Table B-1**; and **Section 2.5.2.3**).

<u>Example</u>: 1

What is a product's performance (indicator) in terms of recycling rate and recycling-orientation? Hint: The product has Recycling Rate = 60, and Recycling Orientation = 65.

<u>Solution</u>

(1) Recall (**Equation 1**) $PI = [RR \text{ x } RO]^{1/2}$

(2) Substitute the value of RR and RO into (**Equation 1**), which yields:

$$PI = (60 \text{ x } 65)^{1/2}$$

$$= (3,900)^{1/2}$$

$$\therefore PI = 62.45 \qquad \underline{\text{Ans}}.$$

PI can also plotted and displayed on a 3-D graph, which comprises x-axis, and y-axis, (in this case, z-axis = 0). The x-axis represents for the Recycling Orientation and the y-axis represents for the Recycling Rate, each axis has the scale between 0 and 100 (see **Figure 4-50**).

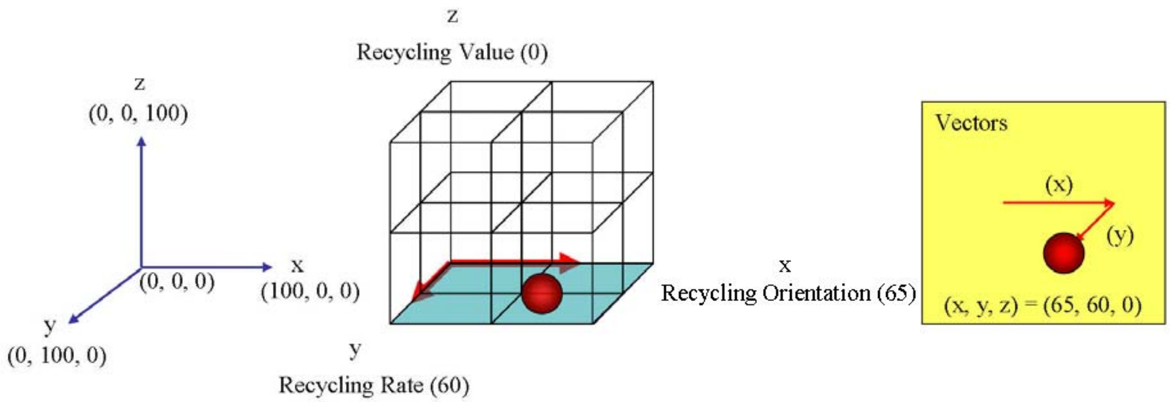


Figure 4-50: Performance Indicator (PI), 3-D.

4.11.4.2 Recycling Indicator (RI)

Recycling Indicator (RI), takes Recycling Rate (RR), Recycling Orientation (RO) and Recycling Value (RV) into consideration. This indicator is a display of the geometric third (cube) root of the three variables: RR, RO, and RV. Legislations normally stipulate the RR of the products. The RO is used as a determinant for reuse/recycle/disposable parts, and for optimizing the EOL benefits. RO reveals the opportunity for product recycling, which plays a very important role for (1) recyclers' sustainability, (2) the manufacturers' sustainability; when the recycling-orientation of product design are improved and when take-back and recycling programs are realized. Products with high RO ease and facilitate dismantling processes; and indicates high retrieval potential of the reusable parts/materials. Global players usually set their product development goals not only in conformity with legislations, but also within the framework of EOL management. In developing countries where recycling related issues, typically receive no subsidies, economic issues receive the highest priority above all product characteristics, in order to ascertain recycling viability.

RR, RO, and RV, are often considered simultaneously; therefore, a medium that equally shares these three important attributes and intrinsically expresses them as an absolute value, as does "Recycling Indicator," (RI) could be the answer for rating products. The following equation expresses the relationship of RI with RR, RO, and RV:

$$\text{Recycling Indicator} = [\text{Recycling Rate x Recycling Orientation x Recycling Value}]^{1/3}$$

$$\text{RI} = [\text{RR x RO x RV}]^{1/3} \qquad \leftarrow(\textbf{Equation 2})$$

where RI = Recycling Indicator; RR = Recycling Rate; RO = Recycling Orientation; RV = Recycling Value; and RR, RO, RV ≥ 0.

RI can be plotted on a 3-D graph, which comprises x-axis, y-axis, and z-axis. The x-axis represents Recycling Orientation, the y-axis represents Recycling Rate, and the z-axis represents Recycling Value. Each axis has a scale between 0 and 100. RI primarily has two-axis based (x, y) similar to PI, which can display the "Product Performance Indicator," beyond that when considering Recycling Value (vertical axis, z-axis) the new product indicator can be found. The "Product Recycling Indicator" displays the characteristics of the product from the perspectives of three variables, which also take the product costs (selling/purchasing price, and EOL benefits) into account (see **Figure 4-51**). The vertical axis, z-axis, shows the economics of the product: including product devaluation. The higher the value in the z-axis, the higher the possibility to get more money at the product's EOL.

Example: 2

What is a product's recycling indicator in terms of recycling rate, recycling-orientation, and recycling value? Hint: The product has Recycling Rate = 60, Recycling Orientation = 65, and Recycling Value = 75.

Solution

(1) Recall (**Equation 2**) $\quad \text{RI} = [\text{RR x RO x RV}]^{1/3}$

(2) Substitute the value of RR, RO, and RV into (**Equation 2**), which yields:

$$\text{RI} = (60 \text{ x } 65 \text{ x } 75)^{1/3}$$

$$= (292{,}500)^{1/3}$$

$$\therefore \text{RI} = 66.38 \qquad \underline{\text{Ans}}.$$

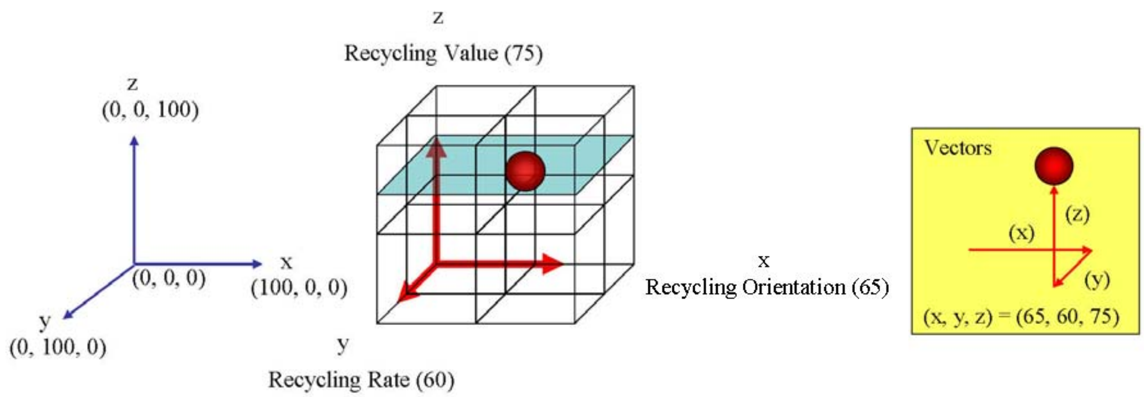


Figure 4-51: Recycling Indicator (RI).

4.11.5 Report Common Function

ReOAT's reports have six functions in common:

1. *Toolbar.* The report tool, contains 12 functions: (1) Go To First Page, (2) Go To Previous Page, (3) Go To Next Page, (4) Go To Last Page, (5) Go To Page, (6) Close Current View, (7) Print Report, (8) Refresh, (9) Export Report, (10) Toggle Group Tree, (11) Zoom, and (12) Search Text (see **Figure 4-52a**).
2. *Export report*. Users have six different file type options to export the report file: (1) Crystal Reports *.rpt, (2) Adobe Acrobat *.pdf, (3) Microsoft Excel *.xls, (4) Microsoft Excel Data Only *.xls, (5) Microsoft Word *.doc, and (6) Rich Text Format *.rtf) (see **Figure 4-52b**).
3. *Zoom*. Zoom options e.g., page width, whole page, 400%, 300%, 200%, 150%, 100%, 75%, 50%, 25%, and customize are available (see **Figure 4-52c**).
4. *Zooming*. Customize zooming within the rage of 25-400% scale (see **Figure 4-52d**).
5. *Search*. Search text within a report (see **Figure 4-52e**).
6. *Print.* Print the report out (see **Figure 4-52f**).

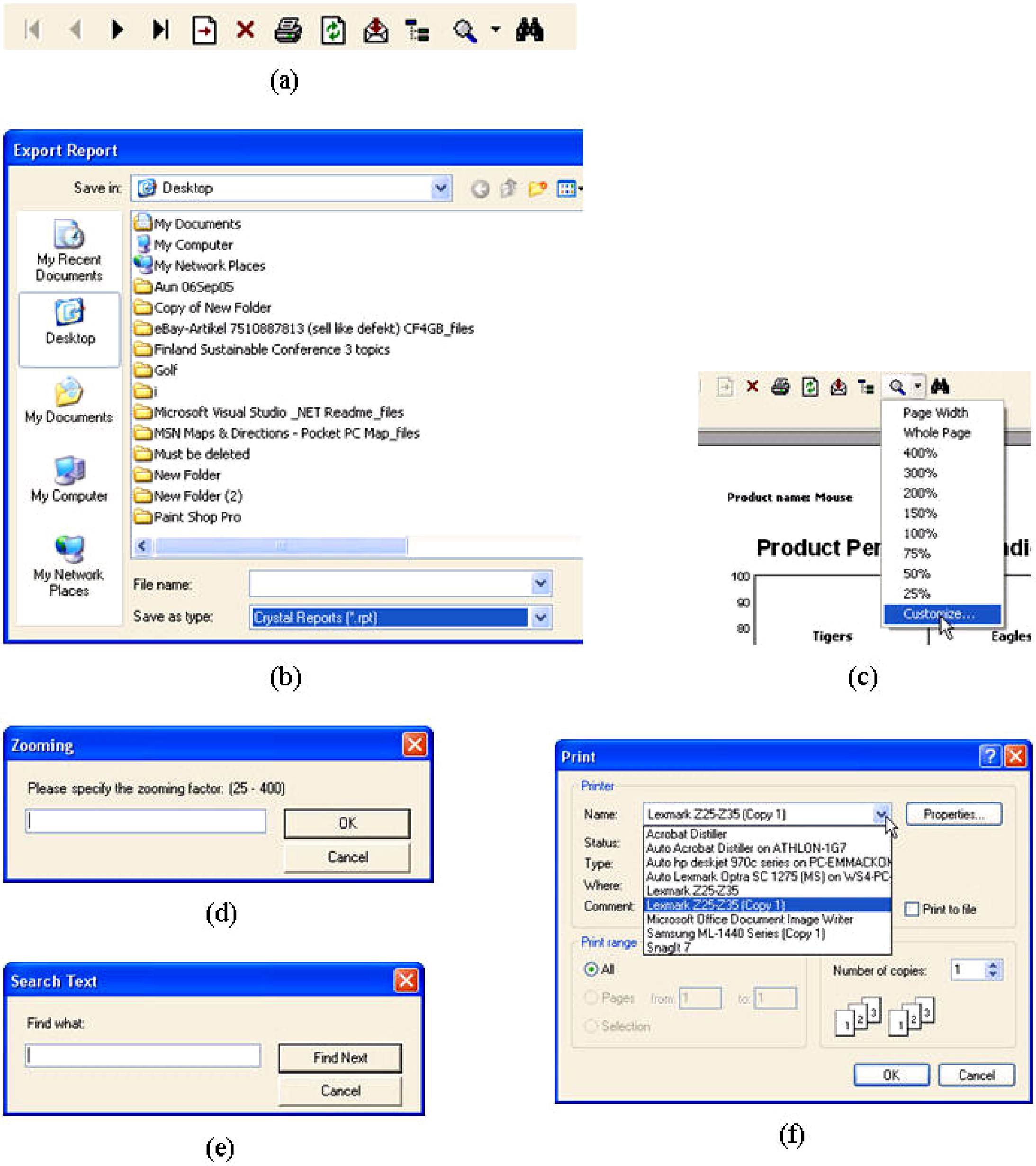


Figure 4-52: Report common functions: (a) toolbar, (b) report export, (c) graph zoom option, (d) graph customize zoom, (e) search text, and (f) print.

Chapter 5

Recycling-Oriented Assessment Tool

5.1 Introduction

This chapter distills concepts and results of all the preceding chapters into an integrated prototype system, called the “Recycling-Oriented Assessment Tool,” or ReOAT. ReOAT uses a shared object-oriented database as a core data, and an integrated project planning system that includes (i) an interface to an intelligent program, (ii) the concept of disassembly technology, (iii) ReOAT procedure, (iv) product model administration, and (v) reporting. The following sections describe the ReOAT system, its various applications, and provide an example of a product sample using the system.

5.2 The Concept of Disassembly Technology – gateway to recycling

Currently, composite and complex consumer products and durable goods like cars at their end-of-life are sent to shredding facilities for processing, in order to retrieve valuable parts/materials before the residues are disposed of. Unlike cars which contain mainly metals fraction; household appliances, electrical and electronic equipments comprise more variety of fractions e.g., metals, plastics, valuable/recyclable/hazardous materials/parts. VDI standard 2243 has categorized the recycling of used equipments into two pathways: (1) remanufacturing (through production technology), and (2) processing (through material technology) (see **Figure 5-1**). Used equipments remanufacturing is preferred by recyclers to used equipment processing. While used equipments processing yields secondary raw materials, and usually degrades qualities, used equipments remanufacturing preserves product value.

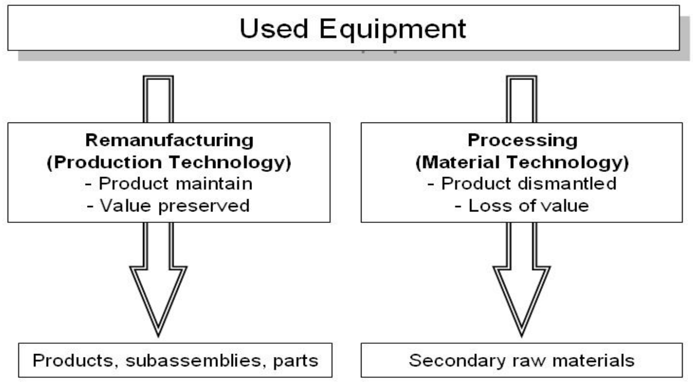


Figure 5-1: Type of recycling (VDI 2243) (source: Ertel, 2002).

Today’s state-of-the-art of shredding processes only allow efficiently recover of metals, with limitation on plastics recovery because variety of plastic types used in various products are often unidentified. Mixed recycled plastic materials are usually degraded because mixed plastics are not compatible with recycling.

Tomorrow’s technologies could allow recovery of other material fractions, more efficiently and economically e.g., (1) “Self-disassembly mechanisms.” Nokia Research Center, Finland, are developing self-disassembly mechanisms for a device to be opened automatically with an outside triggering force such as temperature, magnetism, and chemical & biological decomposition; while preserving the integrity of the devices main components (Tanskanen, 2002). (2) “Automatic dismantling system.” A system, integrated CAD/CAM environment for evaluating products cost for assembling and disassembling parts at their design phase by the virtual manufacturing of products’ manufacturing and de-manufacturing processes (Swee, 2001). (3) “Automatic dismantling robot.” Model parts of connection elements like screws are automatically dismantling by the robot. Using a computing power with the real-time image processing, a multi-level 3-D tracking approach, with a camera and a powered screwdriver mounted on the robot hand, Visually Servoed Dismantling Operations of used Mobile Vehicles (VISDOM) (Gengenbach, 1996; Nagel, 2005).

Although there are many good signs (e.g., past achievements, ongoing researches, new modeling, prototyping) for tomorrow technologies, there is much to be resolved regarding limitations e.g., (1) Product and manufacturing design constraints of self-disassembly innovative products, such as property of materials and joint mechanisms, total design regarding strength, durability, life-time, and cost. (2) The dreadfully large CAD/CAM products & processes' design database, which are required to be collected on variety of commercial products for the automatic dismantling system. (3) R&D of the automatic dismantling robot for the real-time image processing to recognize more variety of materials & joint types with constraints such as: speed, technique, precision, and cost. Automatic disassembly technologies will not truly become feasible until there are breakthroughs with these constraints. Therefore, currently the manual disassembly technologies are more practical when variety of products are involved, than the automatic disassembly technologies

At the Department of Industrial Sustainability, BTU Cottbus, Germany, research into the method of manual disassembly technologies and product design assessments, has been advancing, regarding the determination of products' recycling rate, disassembly time, economic value, and design recommendations. Studies of product design involving household electrical and electronic appliances were carried out e.g., dishwashing machines, vacuum cleaners, mobile phones, cooking machines, automotive fuel pumps, etc. To be familiar with the manual disassembly technologies, an example of dismantling analysis of automotive fuel pumps is taken and being explained as follows. The fuel pump project's objective was to find out, the potentials for product environmental improvement, and subsequently make design recommendation. The disassembly process was carried out. During the disassembly process, pictures (sequence), which displayed the dismantling processes systematically were taken (see **Figure 5-2[1-12]**).

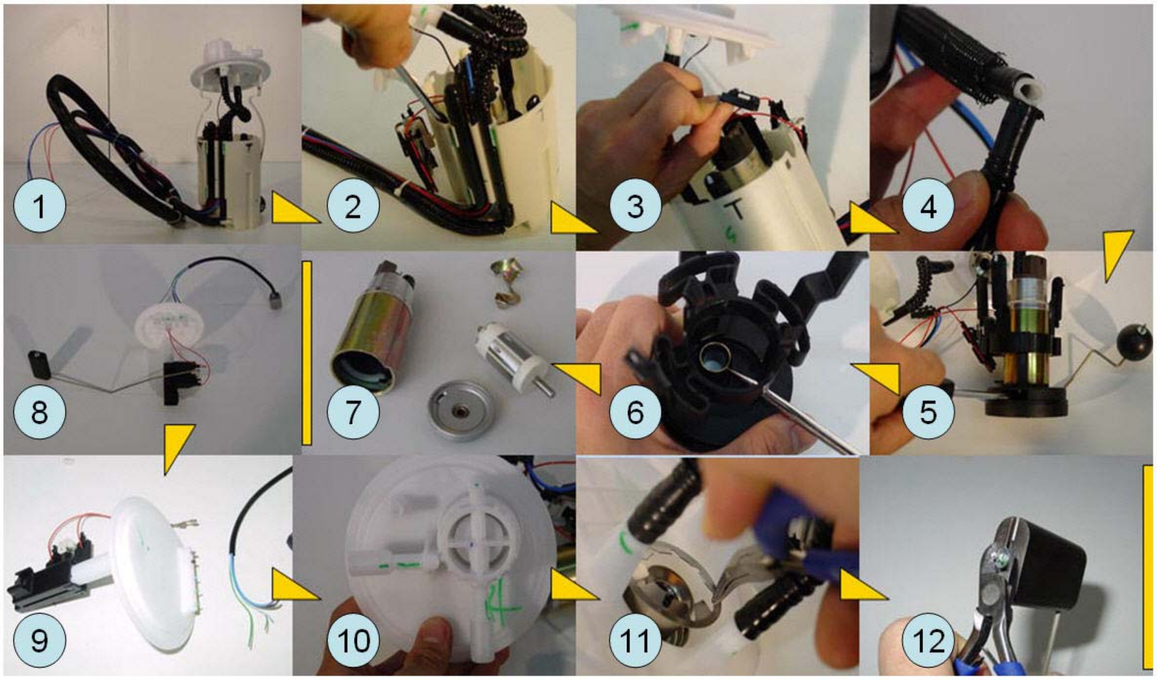


Figure 5-2: Disassembly analysis (source: modified from Wongdeethai, 2003).

The instruct number of sub-figures illustrated the succession of the product before break down (dismantling) until completion of the operation. Necessary product profiles were collected, systematically during the dismantling process, pictures were taken for documentation and for crosschecking e.g., when there is a need to identify item (part/assembly) specifications, its locations/connections. Afterwards, these information were inserted into product design software for assessing the concerned issues. Later, the results, remarks, and difficulties during the study were recorded, and discussed. Finally, the conclusion and recommendations were drawn.

Experiences gained and lessons learned during carrying out these studies i.e., feasibilities and difficulties were recorded and compared by utilizing a number of products design assessment softwares. From the studies, it was found that, marketed softwares were complicated, some functions were redundant, not really employed, and not totally flexible. These issues had been noted, and remarked for future improvement. Later, a new system and models were formulated by taking the remarks into account which are considered in this dissertation. Commercial softwares, and their limitations were described in **Section 1.2.1**, the solution and method are described in **Section 1.2.2**, and **Section 1.2.3**, respectively. The proposed architecture program solution or ReOAT, its procedure, how it is used, how the results can be interpreted, will be elucidated with an example, in the following sections.

5.3 ReOAT Procedure

The ReOAT software is a useful tool for the inventory of product profiles and for assessing recycling-related issues, for instance the following frequency asked questions on product disassembly analysis could be answered by using ReOAT: (1) What are product parts, assemblies? (2) How are they connected to each other? (3) What are the fractions of valuable parts, materials, waste, hazardous items? (4) What is the product optimal EOL scenario? and (5) Are there any possibility to enhance the product performance, and how?

The "Methods," often called the "Procedures," discusses how the determination processes are done. Documenting the procedures of the product project is important not only for the reason that others can repeat the results but also that the first user can replicate the work later, if the need arises. The ReOAT's procedure is a systematic deterministic process, which has been formulated, to serve specific purposes.

An automotive navigation software is taken as a platform for demonstration and comparison with ReOAT's procedure. A build-in intelligent car driving assistant and control system which has several manoeuvring functions incorporated with panel displays, and control units such as: speedometer, revolutions per minute (rpm) meter, engine temperature displayed, gear indicator, cooling liquid and engine oil level indicators, cruise control, lightings systems, navigation system, etc., is being likened to ReOAT. The central control units (system) employed the power of computer chips and several sensors. It guides and facilitates a driver's decisions by means of a computer software. For example, when a driver (software user) wants to drive from one place to visit friends in other places, the user chooses the starting point and the final destination, (as coordinates in the global position system or GPS), the software will delineate known roads (from its database) linking the two defined positions, (available roads are delineated in terms of: names, distances, and directions). The software also explores roads under construction, as well as roads under consideration for future construction within specified province(s), country(s), or region(s).

The ability and the power of computer and the software technology can combine all information together and compute the most appropriate route from the starting point to the destination. As in advanced automotive built-in navigation system, where the driver may have options to select his own choice based on particular needs, the software provides functions and options to determine: (1) the shortest distance (take mainly rural roads with speeds limited); (2) route which stick mainly to main roads/motorways to save maintenance cost – quality of roads are better (usually take longer distance but shorter in time – cars are allowed to run at a higher speed, when no traffic jam); (3) customize route (users define transmission stops); (4) the shortest time (combination of all available roads to find the shortest time); (5) the most economic route (calculate least fuel consumptions, regardless of time spend); and (6) the optimal route (select the ultimate choice to compromise all options: shortest time, shortest distance, pass the defined transmission points, and most economic).

Similarly in disassembly analysis, disassembly pathways (options) exist for achieving different goals. ReOAT provides ability to select an optimal choice e.g., select the ultimate choice to suit all defined options such as: the shortest disassembly time (save personal cost), the lowest disposal cost, and the highest recycling profit. In the case problem (see **Section 5.4**), the software found the optimal pathway for disassembling the product. It should be noted that, it is not always necessary to disassemble to the very single parts, because some parts have recycling benefits while others do not.

The ReOAT procedure is regard as a process flowchart for finding optimal solution, which is illustrated in **Figure 5-3**.

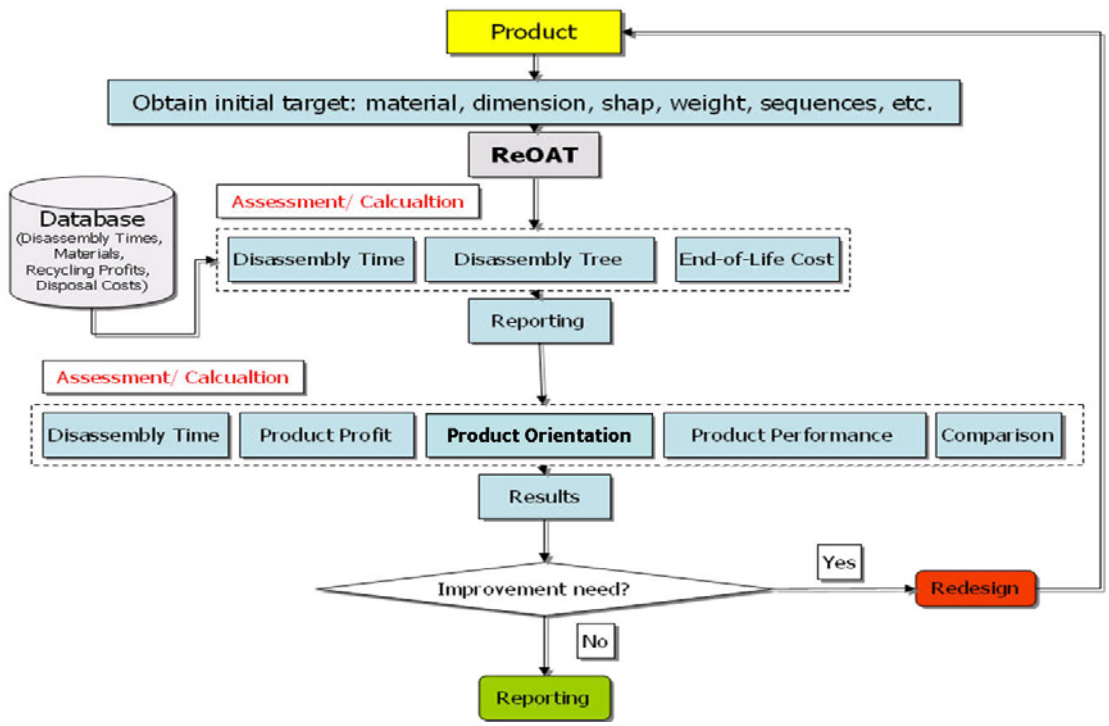
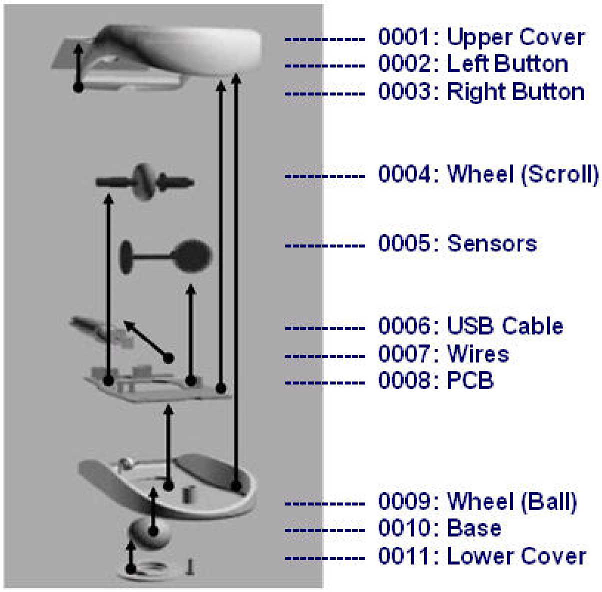


Figure 5-3: ReOAT procedure.

First and foremost, the product information is necessary; the assessment cannot be accomplished correctly without good quality product data. Usually, product profiles and product information are absent for consumers, therefore the software procedure starts with seeking the necessary information, through to obtaining the optimal solution by following three-steps. **Step I**: Obtain the product profiles. Dismantling the product to get records of product profile entries e.g., material, shape, weight, joint type, and sequence and insert them into the software interface. **Step II**: Structuring the product model. With the aid of software's algorithms and database communication, the following product assessment results can be obtained e.g., product's disassembly tree, disassembly time, and EOL costs. These results will be used extensively to address core topics of complete disassembly, and optimal disassembly including: disassembly time, product profit, recycling orientation (recycling oriented product design), product performance indicator, and comparison (benchmarking products). **Step III**: Interpret the results. Essentially, these results will be evaluated and interpreted by users (e.g. designers) in terms of potential improvements, design recommendation. When there is a potential for product improvement, the users can virtually adjust the product model according to their new design, and see the results concurrently. Finally, when the modification and the results of the new model are satisfied, the reports (printouts from the software) can be made available.

5.4 Case Problem: Wheel Mouse

Case problem: wheel mouse, is mainly used to demonstrate how users can use ReOAT to accomplish project goals by following the ReOAT's procedure. It displays how stuffs work. The case problem: wheel mouse, consists of 11 parts: (1) Upper Cover, (2) Left Button, (3) Right Button, (4) Wheel (Scroll), (5) Sensors, (6) USB Cable, (7) Wires, (8) PCB, (9) Wheel (Ball), (10) Base, and (11) Lower Cover. The goals of the study are to find out the product status at EOL (cost), recycling rate, etc. The product structure of the wheel mouse is simple and easy to understand. A more complicate product, that comprises many parts and different joint types can be modeled by using the same system following the same procedure. In order to get a better understanding of the contents of the wheel mouse, the dissection "exploded-view," is displayed (see **Figure 5-4a**).



(a)

No.	Predecessor	Successor
1	0001: Upper Cover	0011: Lower Cover
2	0001: Upper Cover	0002: Left Button
3	0001: Upper Cover	0003: Right Button
4	0001: Upper Cover	0004: Wheel (Scroll)
5	0001: Upper Cover	0006: USB Cable
6	0001: Upper Cover	0007: Wires
7	0004: Wheel (Scroll)	0005: Sensors
8	0005: Sensors	0008: PCB
9	0006: USB Cable	0008: PCB
10	0007: Wires	0008: PCB
11	0008: PCB	0009: Wheel (Ball)
12	0009: Wheel (Ball)	0010: Base
13	0010: Base	0011: Lower Cover

(b)

Figure 5-4: The wheel mouse: (a) exploded-view; (b) disassembly sequences.

The wheel mouse's product data profiles are collected during the dismantling process; the data quality of product profiles plays an important role in the accuracy of assessment and results. When a study product is more complicate for disassembly e.g., an automotive fuel pump with more than 40 parts (Wongdeethai, 2003); a dishwashing machine with more than 150 parts (Dörre, 2002), the products' inventories are large and may need cross-checking to identify parts and their properties in order to ensure the accuracy. Balancing of product's weight before and after the dismantling operation can be used to certify that there is no part missing from the operations. In order to assess the recycling-orientation of product design of the wheel mouse; the three-steps of ReOAT's procedure are used, and described in the following sections.

5.4.1 Step I: Obtain the Product Profiles

Step I: Obtain the product profiles. After dismantling (in this case), and/or data obtained from product's manual/document, the wheel mouse's profiles are tabulated and described as: (1) Parts/assemblies attributes e.g., name, shape envelop, dimension, accessibility, direction, material, weight, and marked) (see **Table 5-1**, and **Figure 5-5**); (2) Joint types e.g., top part, base part, joint type, specification, disassembly tool, and quantity (see **Table 5-2**); and (3) Sequences of disassembly (predecessor, and successor) (see **Figure 5-4b**). Later on the data which are illustrated in **Table 5-1**, **Table 5-2**, and **Figure 5-4b**, will be inserted into the software for further calculation.

Table 5-1: The wheel mouse: parts and materials attributes.

No.	Part	Shape Envelop	Dimension (mm)	Accessibility	Direction	Material	Weight (g)	Marked
1	Upper Cover	Flat Rectangular	90	Excellent	Vertical	Plastic (ABS)	19.00	Yes
2	Left Button	Flat Rectangular	45	Excellent	Vertical	Plastic (ABS)	3.00	Yes
3	Right Button	Flat Rectangular	45	Excellent	Vertical	Plastic (ABS)	3.00	Yes
4	Wheel (Scroll)	Flat Cylinder	20	Excellent	Vertical	Plastic (Unidentified)	4.50	No
5	Sensors	Box	10	Poor	Vertical	Plastic (Unidentified) + IC	1.30	No
6	USB Cable	Cylinder Rod	1,200	Excellent	North	Insulated Wires	31.00	No
7	Wires	Cylinder Rod	20	Excellent	Vertical	Insulated Wires	1.10	No
8	PCB	Flat Rectangular	35	Excellent	Vertical	PCB	14.00	No
9	Wheel (Ball)	Box	25	Poor	Vertical	Metal + Epoxy Coated	32.00	No
10	Base	Flat Rectangular	90	Excellent	Vertical	Plastic (ABS)	19.50	Yes
11	Lower Cover	Flat Rectangular	35	Excellent	Vertical	Plastic (ABS)	1.50	Yes

For the explanation of the shape envelop, see **Section** 4.8.7.3. Parts' dimensions are initially measured in length, width, and height (L x W x H) (mm). That are recorded in the disassembly protocol (product profiles documentation before inserting these data into the software). However, users need to insert only the longest dimension of each part into the software, for the purpose of parts' identity verification. The direction of the disassembly axis (north, south, east, west, and vertical) is used for the purpose of parts' identification, as well as establish different disassembly time (see **Table A-28**).

The wheel mouse materials composition is described in the following figure.

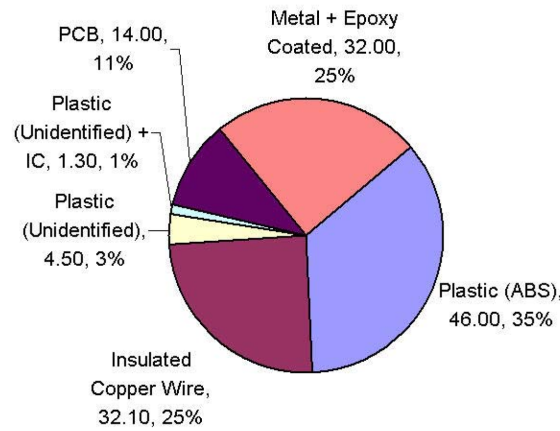


Figure 5-5: The wheel mouse: materials composition in percentage.

The major composition are: (1) Plastic (ABS) 35%, (2) Insulated Copper Wires 25%; (3) Metal + Epoxy Coated 25%; and PCB 14%. See also in **Section 5.4.3.1** for additional information used in the disassembly assumption of the wheel mouse

Table 5-2: The wheel mouse: joint types.

No.	Top Part	Base Part	Joint Type	Specification	Disassembly Tool	Quantity
1	0001: Upper Cover	0011: Lower Cover	Screw connection	Screwdriver against cross-recessed	Screwdriver against cross-recessed head screws	1
2	0001: Upper Cover	0002: Left Button	Snap fastener	Type A	Tooless	4
3	0001: Upper Cover	0003: Right Button	Snap fastener	Type A	Tooless	4
4	0001: Upper Cover	0004: Wheel (Scroll)	Snap fastener	Type A	Tooless	2
5	0001: Upper Cover	0006: USB Cable	Embody/contact	Together	Tooless	1
6	0001: Upper Cover	0007: Wires	Embody/contact	Together	Tooless	1
7	0004: Wheel (Scroll)	0005: Sensors	Sliding joint	-	Tooless	2
8	0005: Sensors	0008: PCB	Soldered joint	-	Diagonal cutting nipper	2
9	0006: USB Cable	0008: PCB	Snap fastener	Type E	Pliers	2
10	0007: Wires	0008: PCB	Soldered joint	-	Diagonal cutting nipper	1
11	0008: PCB	0009: Wheel (Ball)	Embody/contact	Together	Tooless	1
12	0009: Wheel (Ball)	0010: Base	Embody/contact	Together	Tooless	1
13	0010: Base	0011: Lower Cover	Snap fastener	Type C	Tooless	2

Cross references:

1. The disassembly sequence, is described in **Section 5.4.2.8**.
2. The illustration of what is Top part, and Base part, is described in **Figure 5-4b**.
3. Joint type is described in **Section 4.8.7.5**.
4. Disassembly tool is described in **Section 4.8.7.21**.

5.4.2 Step II: Structuring the Product Model

Regardless of whether the data of product profiles has been partially or completely obtained, the product model can be built, because the software allows users to add, edit, and delete, the information of product models in the software at anytime. It is also possible to model the product virtually, as a prototype, to forecast the product properties before to make the real product. In the following sections, instructions have been provided accompanied by diagrams to explain users how to use the ReOAT system for structuring the product model.

5.4.2.1 Start ReOAT

For first time users, follow the ReOAT instruction for software setup until installation is completed. Users can open the software in different ways e.g., triggering (1) the ReOAT's start command, (2) shortcut, or (3) application itself. Instantly, after triggering the command, the software will initiate the ReOAT splash page that displays the software version, and background data loaded, and thus ready for exercise (see **Figure 5-6**).

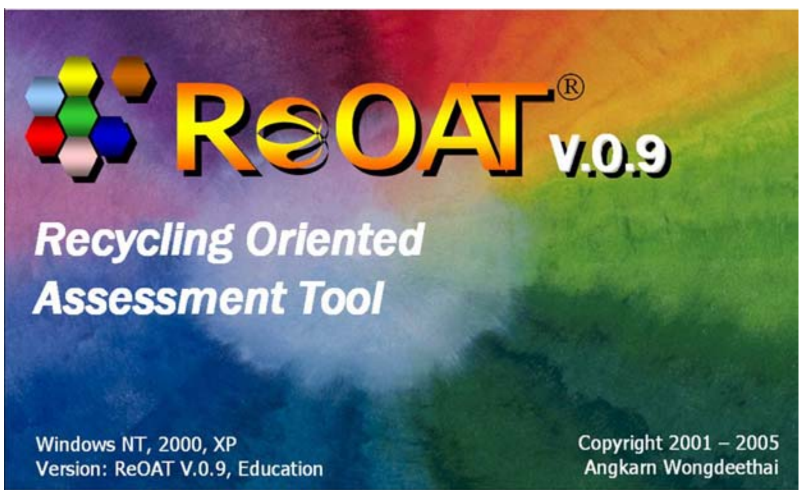


Figure 5-6: Splash screen, ReOAT V.0.9.

The ReOAT system comprises eight models, each of which is specifically designed for different assignments, all menu interfaces have been simplified for easy to use and recognition of its functions (as described between **Section 4.4** and **Section 4.11**). The software is flexible for updating; e.g., add, edit, and delete the data from database; these commands could be evoked across menu bars. There is more than one pathway to access information within the software (see **Figure 5-7**).

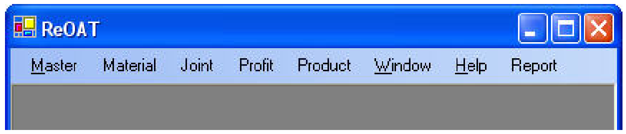


Figure 5-7: ReOAT system.

When ReOAT is opened, the name of the current activated model/menu is displayed on the upper left corner of the main menu. The dropdown menus are just locate below this (see **Figure 5-8**).

Figure 5-8: ReOAT current activated model/menu name.

5.4.2.2 Opening an Existing Product Model

When the product/project is large, and complex, a certain amount of times is required to structure the product and complete the assessment. In most cases, the software will automatically save when information is added, edited, and deleted. A manual save function is also provided when more than one sub-screen (windows) are in used (activated). In the case that information of some products parts are identical, to avoid a redundant work of entering repetitive information, the software data integration function enables linking and recall of an existing data from one project to others, this function is useful, convenience, and save valuable time (see **Figure 5-9**).

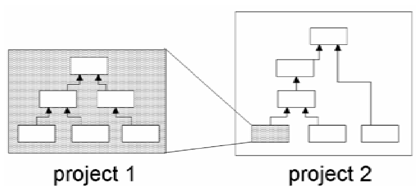


Figure 5-9: Data integration function.

Reuse of existing products models/files prevent processing duplicate parts and setting. The desired product models can be revoked, recalled, and reused at other models; at the menu commands: [Product] > (Material of Item). To view product's sub-directory, at the menu bar click *Products* (expandable box, tree view), and click a desired product (expandable box, tree view), the selected item will be expanded to show its sub-directories. The selected product, when changes are made will automatically be saved, and can be used further in other models (see **Figure 5-10**).

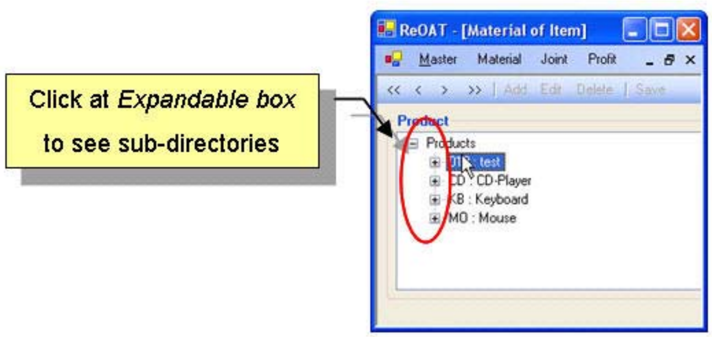


Figure 5-10: [Product] > (Material of Item). Open an existing product model, product tree view.

5.4.2.3 Structuring the Product Model

It is necessary to structure product model and its specific information that covers all necessary information for the assessment. Information entering into the software corresponds to the actual product properties or the design properties (for designers). This information has to be organized and assigned accurately into the product model structure, which consists of parts and assemblies. In the product model structure, a "part" is the smallest unit (item), there is no sub-unit after part, while an "assembly" consists of more than one part, which are connected together. For enhancing the functionality of the product, the study of properties of parts and assemblies helps to determine which product parts/assemblies needed to be improved.

5.4.2.4 Creating a New Product Model

To create a new product model, at the menu commands: [Product] > (Products), (see Figure **5-11**), click *Add*, and fill in the product attributes (*Product ID, Product Code, Product Name, Product Value*). This information can subsequently be modified.

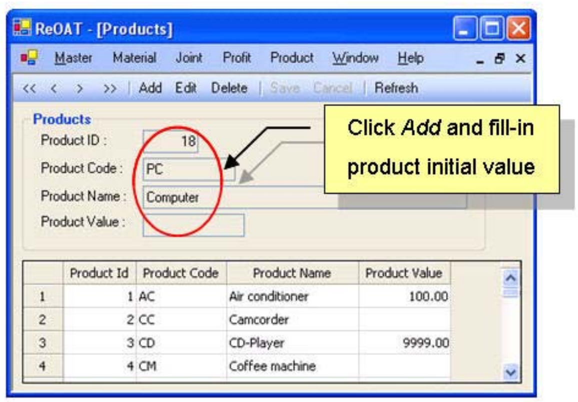


Figure 5-11: [Product] > (Products). Create a new product model.

5.4.2.5 Parts and Assemblies Administration

After the product model has been created; the parts and assemblies can be administered, at the menu command: [Product] > (Item of Product), click *Add, Edit, and Delete*, the product details can then be inserted, modified, and delete (see **Figure 5-12**) accordingly. Basic product's information e.g., *Item of Product ID, Item of Product Code, Item of Product Name, Dimension, Shape, Weight, Accessibility,* can be administered by the users. Add all information of each product parts (11 parts) into [Item of Product].

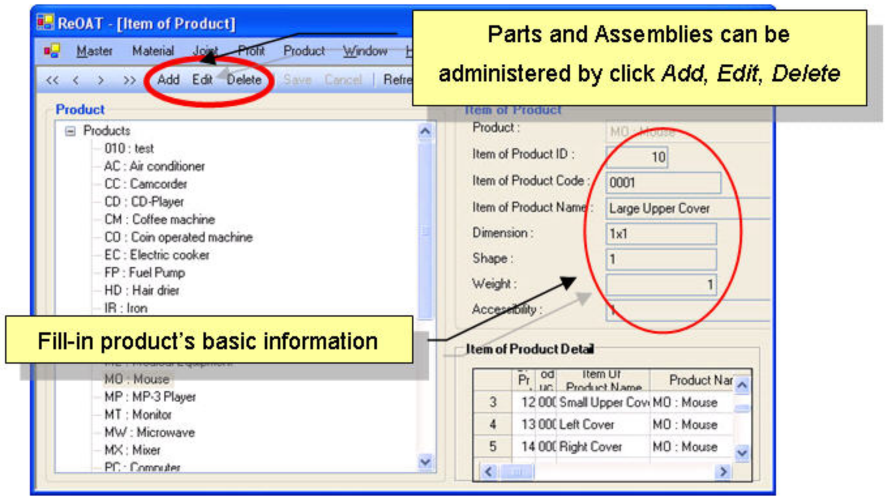


Figure 5-12: [Product] > (Item of Product). Parts and assemblies administration: add, edit, and delete.

5.4.2.6 Materials Administration

After the product's parts and assemblies have been administered, the product material details could be administered subsequently, at the menu command: [Product] > (Material of Item). Select a part to insert material information by clicking *Add*, the product material information e.g., *Product* (categories), *Item of Product, Material*, can be administered (see **Figure 5-13a**). Some information can also be recalled from the existing database (product, item of product, and material) by clicking at the dropdown menu and selecting an appropriate product (see **Figure 5-13b**), and then selecting an appropriate item of product (see **Figure 5-13c**), and administering an appropriate type of material (see **Figure 5-13d**)

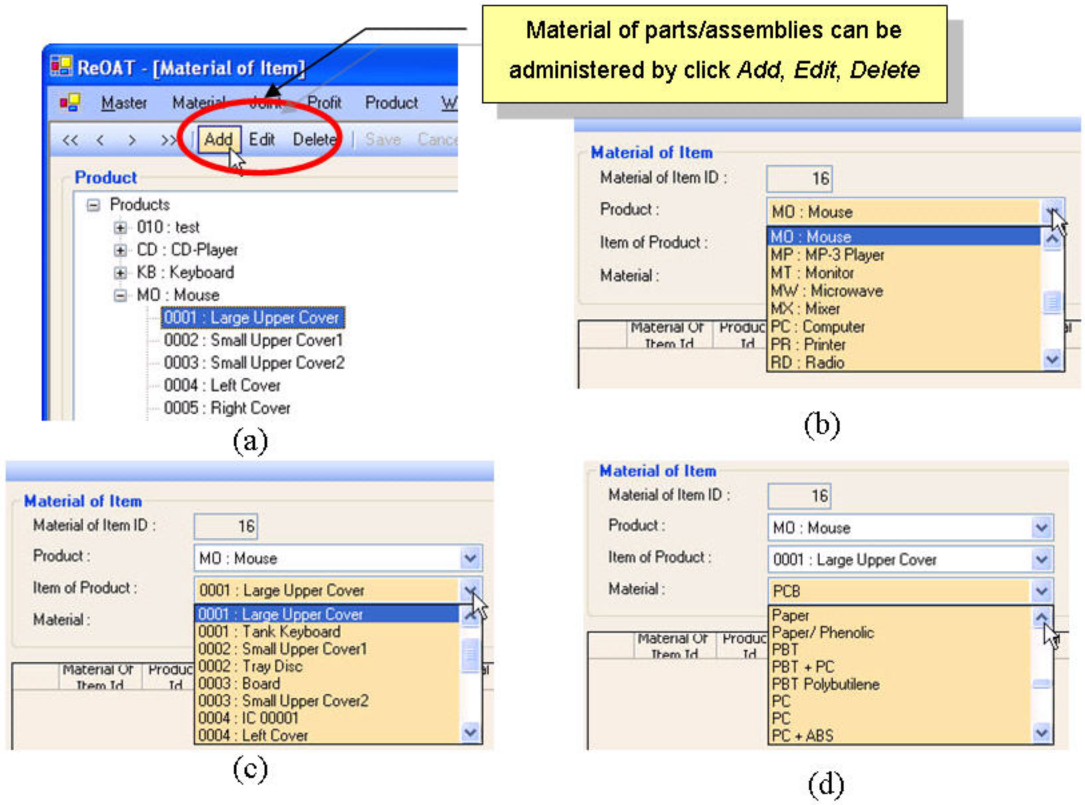


Figure 5-13: [Product] > (Material of Item): (a) administration: add, edit, and delete items; (b) select appropriate product; (c) select appropriate item of product; (d) administer appropriate type of material.

5.4.2.7 Joint Types Administration

After the product's parts and assemblies have been administered, the product joint type details (show how such items connect to each other) could be administered subsequently, at the menu command: [Product] > (Joint Type of Item). The product joint type information can be administered e.g., *Item of Product* (top part), *Item of Product 2* (base part), *Joint Technique* by clicking *Add, Edit, and Delete* (see **Figure 5-14a**). The information can also be recalled from the existing database (item of product, item of product 2, joint technique) by clicking a dropdown menu and selecting appropriate product, then selecting appropriate item of product 2 (see **Figure 5-14b**), and administering an appropriate joint type (see **Figure 5-14c**)

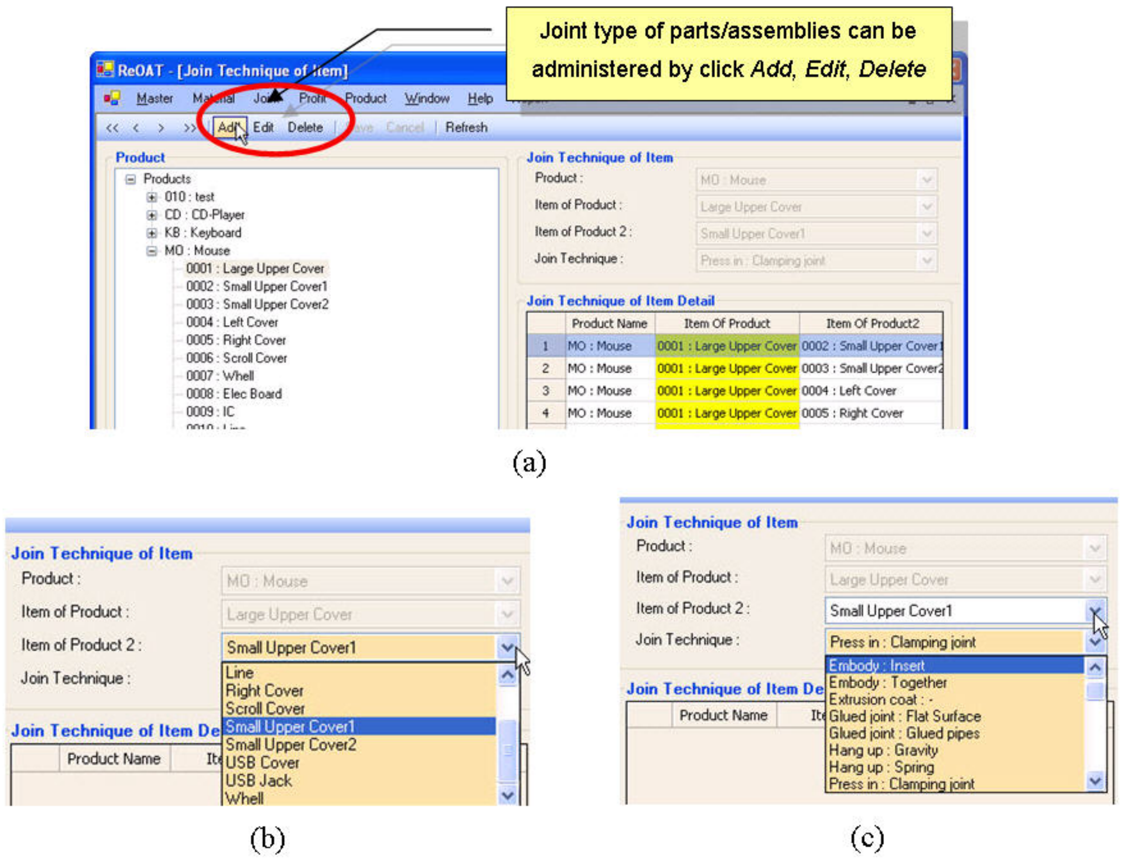


Figure 5-14: [Product] > (Joint Type of Item): (a) joint type administration: add, edit, and delete; (b) select appropriate item; (c) administer appropriate joint type.

Joint between two parts is one of the key issues that play a very important role in recycling-orientation of product design, and ease of dismantling. If Product-A has joint types that facilitates dismantling process more than Product-B, then Product-A has a higher ease of dismantling score than Product-B. The ease of dismantling is among concerned issues that need to be improved in product design, eco-design, or DFR. In ReOAT, there are 14 typical joint types that have been taken into account and made available for users when structuring and modeling products (see **Table A-26**).

Definitions of 14 joint types are:

1. ***Distort***. To connect two parts together by bending two or more wires into a spiral shape.
2. ***Embody/contact***. Locate or assemble two parts together without any joint elements or force.
3. ***Extrusion coat***. Two parts are connected when an extrusion part is bonded/coated by material of another part.
4. ***Glued joint***. Two parts are connected with adhesive substances.
5. ***Sliding joint***. Two parts are connected by inserting a part into another.
6. ***Snap fastener***. Fastening or closing with a click or snap, as a part fitted with a pressure and clicks together.
7. ***Soldered joint***. Use of any of various alloys fused and applied to the joint between metal objects to unite them without heating the objects to the melting point.
8. ***Twist up***. To wind or coil material by rotating or revolving it around a part (as an axis).
9. ***Hang up***. To attach, fasten or suspend a part by placing on a hook, peg, hanger or spring.
10. ***Press in***. Insert, compress or squeeze one part to another by weight or force.
11. ***Screw connection***. Two parts are connected by a fastener having a tapered shank with a helical thread, and topped with a slotted head at one end (type of screw connections, see **Appendix, Figure A-1**).
12. ***Shape joint***. The physical formation shape of a part that has been evolved or developed by hammering, compressing, force, or heat to connect to another part.
13. ***Welding***. Process that the metal part at the points to be joined is melted for joining separate pieces of metal in a continuous metallic bond.
14. ***Wire connection***. A cable used as a conductor of electricity or signal to connect between two parts.

5.4.2.8 Sequence Administration

Not only the joint type between items that has to be identified, but also their disassembly sequences have to be considered, and administered into the software (see **Figure 5-15a**). It is essential to define the sequence of items to the software; this information will enable the software to structure the product model. The product sequences is one of the key factors that enable software to calculate the product complete disassembly as well as optimal disassembly. The illustration of the disassembly sequence of items is shown in **Figure 5-15b**, item of product (Item-1, Top Part) must be removed before reaching the item of product 2 (Item-2, Base Part).

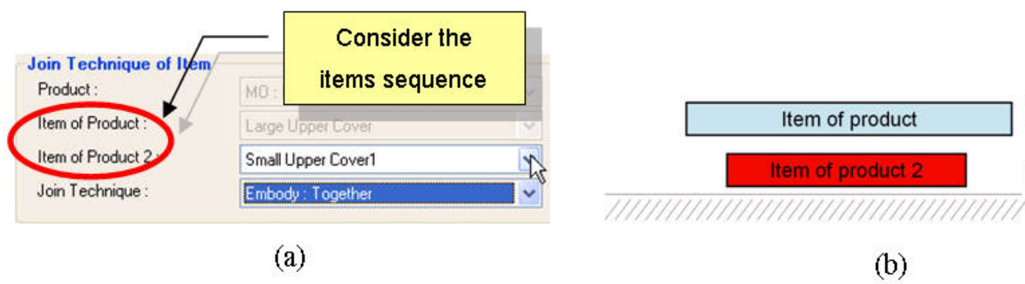


Figure 5-15: Sequence administration: (a) Item sequence; (b) *Item of product* has to be removed first before getting the *Item of product 2*.

5.4.3 Step III: Interpreting the Results

When the product structure has been built and all necessary information of product profiles, materials, joint types, sequences have been administered correctly; the software can then calculate results. The main objective of the software is to deliver and present (report) the product results. The report options can be recalled from the [Report] – model, which provides four different report outputs e.g., (1) [Report Complete Disassembly]; (2) [Report Optimal Disassembly]; (3) [Report Recycling Orientation]; and (4) [Report Performance Indicator] (see **Figure 5-16**).

Figure 5-16: [Report] – model.

The heart of the product study is to obtain the quantitative results, report and understanding those numerical results as well as giving comments and discussion, which are explained in **Step III:** Interpreting the Results. An effective way for presenting numerical results is to show them in graphs; the following sections display and explain (1) disassembly assumption, (2) reports and discussion of the results obtained from the software.

5.4.3.1 Disassembly Assumption

Assuming that the wheel mouse (example) could not be re-sold, reused, or repaired, as it was not functioning. Furthermore it has to be disassembly because there are valuable parts that can be sold for recycling [e.g., Plastic {ABS}, Wheel (Ball) {Metal}], or materials (heavy metals) contain in PCB, Sensors, are considered as toxic materials, which needed to be removed and sent to hazardous landfill, or treatment before disposal.

Let's say, the initial average price of the product (from dealers) at time it was sold was 5 €. The labor cost for disassembling is 20 €/hour. There are two parts that can be sold as reuse parts (consider as a recycle profit), the prices are given as: (1) USB Cable = 0.10 €; and Wheel (Ball) = 0.0060 €. Other parts are selling for the recycling processes according to their market prices. Disassembly cost is calculated from disassembly time x labor cost (see **Appendix, Table A-28**). Disposal cost for hazardous landfill = -164.70 €/ton, and non-hazardous landfill = -16.47 €/ton (Lee, 1995) (see **Appendix, Table A-29**). Transportation costs and taxes are not included in the calculation.

The disassembly is made in such ways that try to retrieve parts, materials at the highest possible quality, i.e., by a non-destructive disassembly approach, unless it has no choice, then a destructive disassembly approach will be used.

The software (this version), has neglected an “energy recovery” pathway, or an “incineration” scenario, because there are many energy recovery technologies which are different on their applications which depend on several variables, constraints, and conditions. Some other softwares make a mistake in their calculation with the assumption of the EOL cost of EOL product by summing up all incurred costs together i.e., [disassembly cost + disposal cost + recycling profit].

As rules of thumb, a matter cannot be at two places at the same time, and no two matters can occupy a space at the same time. After “disassembling,” a part can only be place at one space at a time, in this case, either to “disposal” site, or to “recycling” plant; the EOL cost can be obtained from either (1) [disassembly cost + disposal cost]; or (2) [disassembly cost + recycling profit].

5.4.3.2 Report Complete Disassembly (Report/Graph)

Weight of the product	=	129.90 g
Disassembly Time	=	24.27 s
Disassembly Cost	=	-0.13 €
Disposal Cost	=	0.00 €
Recycling Profit	=	0.13 €
EOL Cost	=	0.00 €

The [Report Complete Disassembly] > (Report), displays essential information of product’s complete disassembly profiles e.g., *Product Name, Item Name, Weight, Disassembly Cost, Disposal Cost, Recycling Profit,* and *End-of-Life Cost*. The complete disassembly of the wheel mouse (example), is described in **Table 5-3**.

Table 5-3: The wheel mouse: list of processing costs of each part (complete disassembly).

Complete Disassembly

Product name : Mouse

Item Name	Disassembly Time (s)	Disassembly Cost	Disposal Cost	Recycle Profit	End-of-Life Cost
0001: Upper Cover	4.66	-0.03	0.00	0.00	-0.02
0002: Left Button	3.50	-0.02	0.00	0.00	-0.02
0003: Right Button	3.50	-0.02	0.00	0.00	-0.02
0004: Wheel (Scroll)	1.17	-0.01	0.00	0.00	-0.01
0005: Sensors	0.99	-0.01	0.00	0.00	-0.01
0006: USB Cable	0.99	-0.01	0.00	0.10	0.09
0007: Wires	0.97	-0.01	0.00	0.00	0.00
0008: PCB	5.48	-0.03	0.00	0.01	-0.02
0009: Wheel (Ball)	0.99	-0.01	0.00	0.01	0.00
0010: Base	1.44	-0.01	0.00	0.00	0.00
0011: Lower Cover	0.60	0.00	0.00	0.00	0.00
Total	**24.27**	**-0.13**	**0.00**	**0.13**	**0.00**

[Report] – model > [Report Complete Disassembly] > (Report).

From the table the number that displayed as 0.00, is not absolute zero, actually it has a value but very small. For demonstration, the digits number used in this table are amplified; six digits number is taken for all column e.g., “Disassembly Time” {column}, “Disassembly Cost” {column}, “Disposal Cost” {column}, and “Recycle Profit” {column}, to illuminate their tiny values (see **Table 5-4**). The negative value means that when the part is processed with the specific operation, the benefit will be lost.

Table 5-4: The wheel mouse: list of processing costs of each part (complete disassembly), illustrates with six-digit number.

Complete Disassembly

Product name : Mouse

Item Name	Disassembly Time (s)	Disassembly Cost	Disposal Cost	Recycle Profit	End-of-Life Cost
0001: Upper Cover	4.660194	-0.025890	-0.000313	0.004139	-0.021751
0002: Left Button	3.495146	-0.019417	-0.000049	0.000654	-0.018764
0003: Right Button	3.495146	-0.019417	-0.000049	0.000654	-0.018764
0004: Wheel (Scroll)	1.165049	-0.006472	-0.000074	0.000082	-0.006391
0005: Sensors	0.990291	-0.005502	-0.000214	0.000008	-0.005494
0006: USB Cable	0.990291	-0.005502	-0.000511	0.100000	0.094498
0007: Wires	0.970874	-0.005394	-0.000018	0.000499	-0.004894
0008: PCB	5.475728	-0.030421	-0.002306	0.014527	-0.015894
0009: Wheel (Ball)	0.990291	-0.005502	-0.000527	0.006000	-0.000498
0010: Base	1.436893	-0.007983	-0.000321	0.004248	-0.003734
0011: Lower Cover	0.601942	-0.003344	-0.000025	0.000327	-0.003017
Total	**24.271845**	**-0.134844**	**-0.004407**	**0.131137**	**-0.003706**

In the table, the data of disassembly cost, disposal cost, and recycle profit of each item are displayed. Each value of the "End-of-Life Cost" {column} in the table is not a summation of all values within the "row," but rather a summation of the selected pathway of individual part within the "row" (the part either goes for disposal cost, or recycle benefit). Each value of the "Total" {row} in the table is not a summation of all values within the "column," but rather a summation of the selected pathway of individual parts within the "column" (the part either goes for disposal cost, or recycle benefit). For example, part No. #0008 (PCB): After the part had been disassembled, the software has to select the best deal from the two EOL scenarios, either "disposal" (-0.0023 €), or "recycling" (0.0145 €). Obviously, "0.0145 €" (recycling) is larger than "-0.0023 €" (disposal), therefore, the "recycling" pathway is selected. Similarly, for other parts that have been selected for the "recycling" partway as their EOL scenario. The final accumulated EOL value, the value in bottommost of the last column, has depicted that the complete disassembly does not pay off; it gives negative benefit (-0.0037 €).

On another hand, these complete disassembly data (**Table 5-3**) can be illustrated in graphic by clicking *View Graph* button, [Report Complete Disassembly] > (Graph) (see

Figure 5-17), which summarizes overall accumulated costs in the disassembly operation e.g., start from first part is dismantled, until the last part had been removed (clear from the operation table).

Complete Disassembly
Product name : Mouse

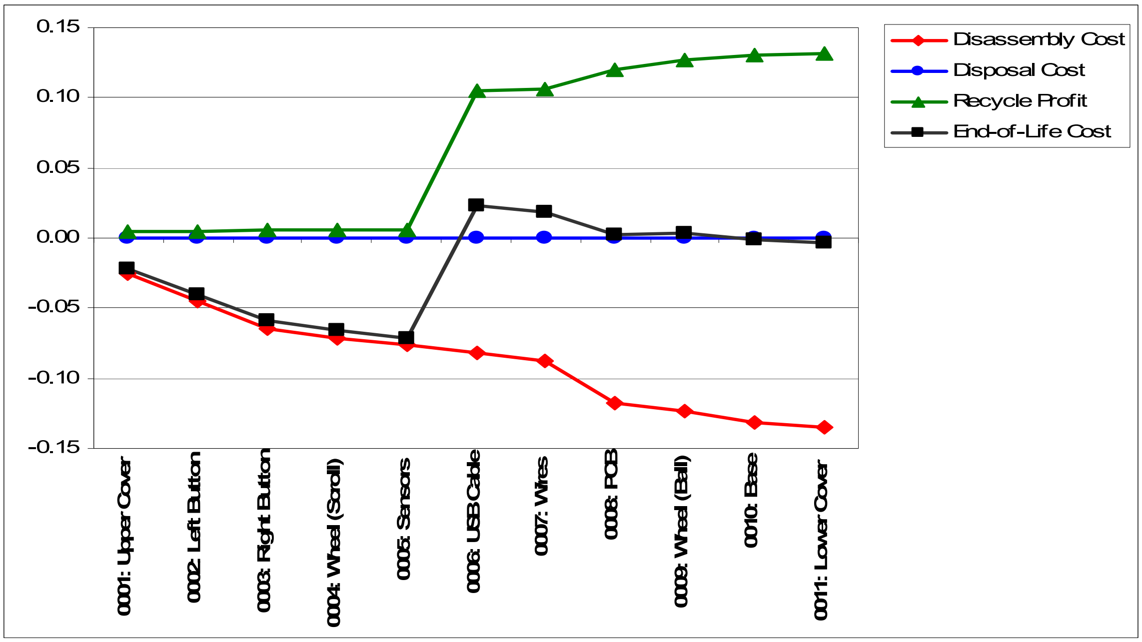


Figure 5-17: The wheel mouse: report complete disassembly.
[Report] – model > [Report Complete Disassembly] > (Graph).

In summary, the final results at the end of each disassembly steps can be investigated from the value of the accumulated EOL cost, (as shown in the figure, ■ End-of-Life Cost). As the accumulated EOL cost is a summation of the selected pathway of the accumulated disassembly cost, the accumulated disposal cost, and the accumulated recycling profit. The EOL cost of the wheel mouse goes negative -0.0221 € right at the beginning when the first part (Upper Cover) is dismantled. It goes more and more negative when the second part (-0.0408 €), the third part (-0.0596 €), the fourth part (-0.0660 €), and the fifth part (-0.0715 €) are dismantled. After that, it rebounded for the first time at the (positive) benefit of 0.0230 € when the sixth part (USB Cable) is dismantled, and down to -0.0181 € when the seventh part (Wires) is removed. After that, it continues going more negatives until the last part (Lower Cover) was removed, which finally ended up at the (negative benefit) cost of -0.0037 €.

5.4.3.3 Report Optimal Disassembly (Report/Graph)

Weight of the product	=	129.90 g
Disassembly Time	=	16.68 s
Disassembly Cost	=	-0.13 €
Disposal Cost	=	-0.10 €
Recycling Profit	=	0.13 €
EOL Cost	=	0.04 €.

The [Report Optimal Disassembly] > (Report), displays essential information of product's optimal disassembly profiles e.g., *Product Name, Item Name, Weight, Disassembly Cost, Disposal Cost, Recycling Profit,* and *End-of-Life Cost*. At the optimal disassembly, the results showed that theoretically three out of eleven parts are not necessary to be dismantled separately, e.g., (1) Left Cover, (2) Right Cover, and (3) Lower Cover, because they can be grouped/bounded and dismantled together with other parts. Parts which have similar material properties e.g., made from the same type of plastic, and are connected together can be grouped/bounded together to reduce unnecessary effort and time to disassemble them. The grouped/bounded parts is named as a "Cluster."

The eleven parts of the wheel mouse have been optimally grouped into eight clusters by the software. The eight clusters are (1) Upper Cover + Left Button + Right Button, (2) Wheel (Scroll), (3) Sensors, (4) USB Cable, (5) Wires, (6) PCB, (7) Wheel (Ball), and (8) Base + Lower Cover. The results of the optimal disassembly of the wheel mouse, is described in **Table 5-5**.

Table 5-5: The wheel mouse: list of processing costs of each part (optimal disassembly).

Optimal Disassembly

Product name : Mouse

Item Name	Disassembly Time (s)	Disassembly Cost	Disposal Cost	Recycle Profit	End-of-Life Cost
0001: Upper Cover	4.66	-0.03	0.00	0.00	-0.02
0002: Left Button	0.00	0.00	0.00	0.00	0.00
0003: Right Button	0.00	0.00	0.00	0.00	0.00
0004: Wheel (Scroll)	1.17	-0.01	0.00	0.00	-0.01
0005: Sensors	0.99	-0.01	0.00	0.00	-0.01
0006: USB Cable	0.99	-0.01	0.00	0.10	0.09
0007: Wires	0.97	-0.01	0.00	0.00	0.00
0008: PCB	5.48	-0.03	0.00	0.01	-0.02
0009: Wheel (Ball)	0.99	-0.01	0.00	0.01	0.00
0010: Base	1.44	-0.01	0.00	0.00	0.00
0011: Lower Cover	0.00	0.00	0.00	0.00	0.00
Total	**16.68**	**-0.10**	**0.00**	**0.13**	**0.03**

[Report] – model > [Report Optimal Disassembly] > (Report).

A part which has the lowest disassembly cost within the cluster is called a "principle part." Within the same cluster, parts other than the principle part will not be considered for their disassembly cost, because they will not be disassembled separately. The disassembly costs of (1) Left Button, and Right Button, and (2) Lower Case are zero because they have not been taken off separately, as they are the members of Cluster 1; and Cluster 8, respectively. The disassembly cost incurred at the Upper Cover, and Base, is the principle part of Cluster 1; and Cluster 8, respectively. Even though, no such a function in this version of the software have been incorporated to display the product clusters by name, and its members names, each cluster can be verified by the position of the zero disassembly cost. For example, Cluster 1: Upper Cover + Left Button + Right Button, has the Upper Cover as the principle part because the following parts: Left Button & Right Button, have no disassembly cost. This is in contrast to the complete disassembly, that involves dismantling every parts of the product, and therefore the disassembly cost is incurred on every part. The recycling profit is always positive because there is revenues when recycling materials/parts are sold (unless part is worthless, or there is payment for the recycling operations). The disassembly cost and disposal cost are always negative (unless it receives subsidies), for the wheel mouse the disposal cost is equal to zero because there were no parts that were actually sent to disposal site, because of the recycle profit option.

The results of the EOL processes in the previous table are very small, which can hardly be noticed. In order to spot the results more clearly the table is displayed in the six-digit number as follows (see **Table 5-6**):

Table 5-6: The wheel mouse: list of processing costs of each part (optimal disassembly), illustrates with six-digit number.

Optimal Disassembly

Product name : Mouse

Item Name	Disassembly Time (s)	Disassembly Cost	Disposal Cost	Recycle Profit	End-of-Life Cost
0001: Upper Cover	4.660194	-0.025890	-0.000313	0.004139	-0.021751
0002: Left Button	0.000000	0.000000	-0.000049	0.000654	0.000654
0003: Right Button	0.000000	0.000000	-0.000049	0.000654	0.000654
0004: Wheel (Scroll)	1.165049	-0.006472	-0.000074	0.000082	-0.006391
0005: Sensors	0.990291	-0.005502	-0.000214	0.000008	-0.005494
0006: USB Cable	0.990291	-0.005502	-0.000511	0.100000	0.094498
0007: Wires	0.970874	-0.005394	-0.000018	0.000499	-0.004894
0008: PCB	5.475728	-0.030421	-0.002306	0.014527	-0.015894
0009: Wheel (Ball)	0.990291	-0.005502	-0.000527	0.006000	-0.000498
0010: Base	1.436893	-0.007983	-0.000321	0.004248	-0.003734
0011: Lower Cover	0.000000	0.000000	-0.000025	0.000327	0.000327
Total	**16.679612**	**-0.096009**	**-0.004407**	**0.131137**	**0.035129**

The graphical view of these results can be recalled by clicking *View Graph* button, [Report Optimal Disassembly] > (Graph). The displayed graphic gives an instant overview of costs & benefits incurred from the optimal disassembly operations (see **Figure 5-18**).

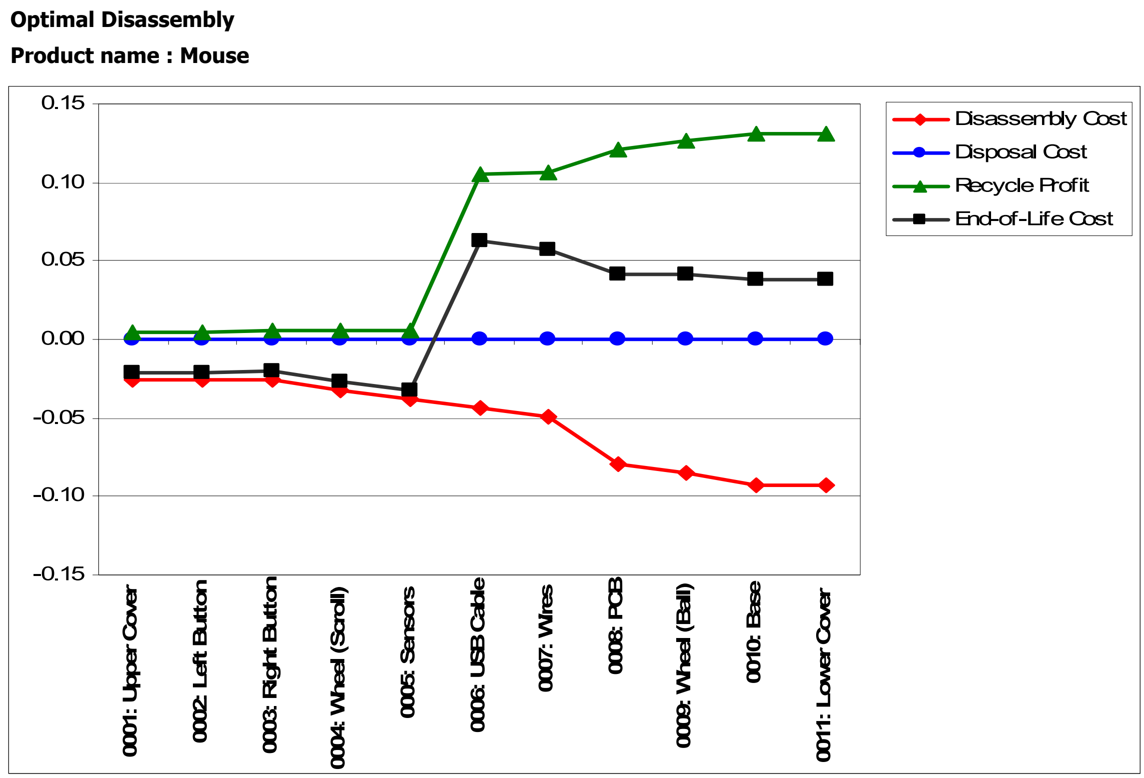


Figure 5-18: The wheel mouse: report optimal disassembly.
[Report] – model > [Report Optimal Disassembly] > (Graph).

From the figure, right at the beginning, the accumulated EOL cost of the disassembling process of the wheel mouse goes negative -0.0218 €, and part No.#0002 and part No.#0003 do not need to be dismantled, because they are member of Cluster 1. After that, the accumulated EOL goes more negative when disassembling Cluster 2 (-0.0268 €), Cluster 3 (-0.0323 €). When Cluster 4 (USB Cable) is dismantled, then the accumulated EOL cost rises up for the first time to a positive benefit of 0.0622 €, this also has the highest benefit that the product can offer, however, the disassembly does not have to stop at this point in accordance with the knowledge that it should continue until Cluster 6 (PCB) is disassembled. The EOL cost of Cluster 5-7 decreases until the last cluster has been removed (Cluster 8) with the final accumulated EOL cost of 0.0351 €.

In summary, the optimal dismantling operation is optimized on the disassembly cost (lowest), the recycling profit (highest), and the disposal cost (lowest) for the wheel mouse. Evidently, the optimal disassembly, which gives an accumulated EOL cost, 0.0351 €, is greater than the final accumulated EOL cost of the complete disassembly, (-0.0037 €). This is because the two dismantling operations pathways are different, and the software uses its algorithms to find the optimal pathway, that avoids unnecessary disassembly pathways.

Obviously, if the dismantling operation ends right after dismantling of Cluster 4 (USB Cable), it will give the highest benefit (accumulated EOL cost = 0.0622 €). However, this is not judicious, because the wheel mouse comprises a printed circuit board "PCB" (Cluster 6), that cannot be directly dispose to non-hazardous landfill. This therefore needs to be dismantled and processed e.g., recycled, treated, or disposed (as special waste).

Generally, used (old) PCB contains hazardous materials and hence cannot be mixed with non-hazardous waste. According to Directive 1999/31/EC, (1999), which states that "non-hazardous" sites can accept only non-hazardous waste, while "hazardous" sites can no longer continue (banned) co-disposal after July 2004 (see also **Section 2.2.3.2**). Therefore, the disassembling operation has to be continue until PCB is removed. Cluster 7: Wheel (Ball) has a recycle benefit (0.0060 €) which is greater than its disassembly cost (-0.0055 €), therefore, it needs to be taken off (dismantled). Lastly, the last cluster (Cluster 8: Base + Lower Cover) remains and needs to be removed from the operation table. Ultimately, the optimal disassembly gives the final accumulated EOL cost of 0.0351 €.

The two results (complete disassembly and optimal disassembly) can be summarized as follows (see **Figure 5-19**):

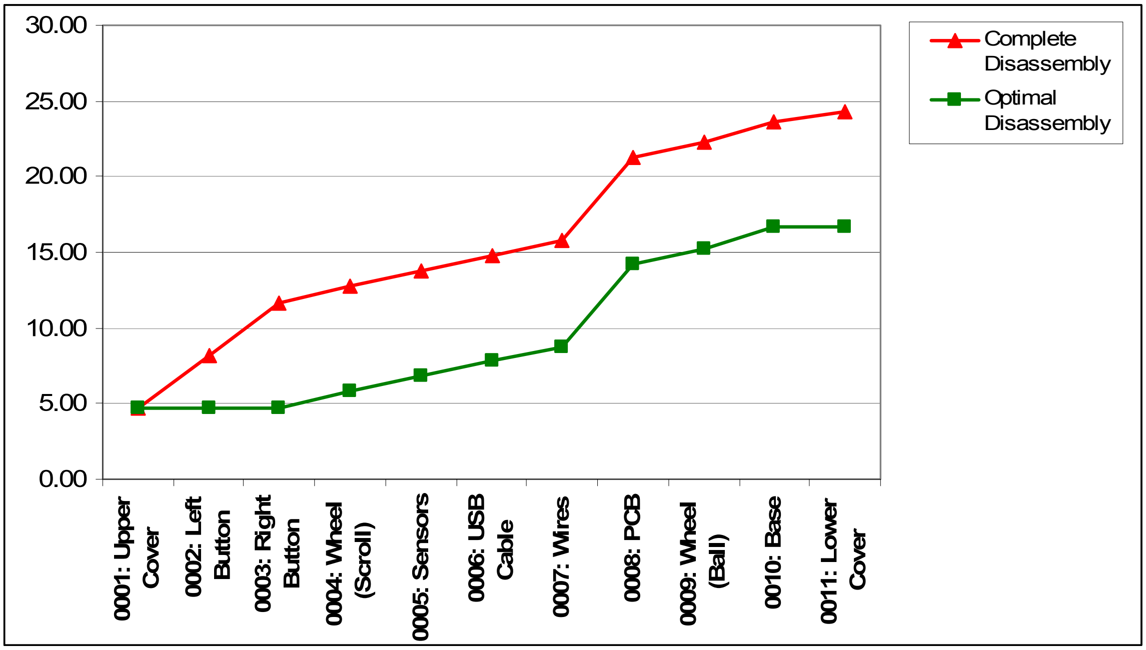


Figure 5-19: The wheel mouse: comparison report of disassembly time (complete disassembly vs. optimal disassembly).

Disassembly Time:	31 % saved	(7.59 s saved)
Disassembly Cost:	29 % saved	(0.038835 € saved)
Disposal Cost:	no difference	
Recycling Profit:	no difference	
EOL Cost:	1,048 % saved	(0.038835 € saved)

Table 5-7: The wheel mouse: comparison report (complete disassembly vs. optimal disassembly).

Disassembly Pathway	Total Time (s)	Disassembly Cost	Disposal Cost	Recycle Profit	End-of-Life Cost
Complete Disassembly	24.27	-0.13	0.00	0.13	0.00
Optimal Disassembly	16.68	-0.10	0.00	0.13	0.04

As shown in **Table 5-7** the comparison of the two different pathways of the wheel mouse, total weight 129.90 g and the economic calculation based on 20 €/hour of personnel cost; evidently the optimal disassembly is more favorable: the optimal disassembly can save more than 1,048 % of the EOL cost, and 31 % of time.

5.4.3.4 Report Recycling Orientation

The [Report Recycling Orientation] displays average values of all product parts' recycling-oriented product design scores graphically (see **Figure 5-20**, and detail in **Table A-1**).

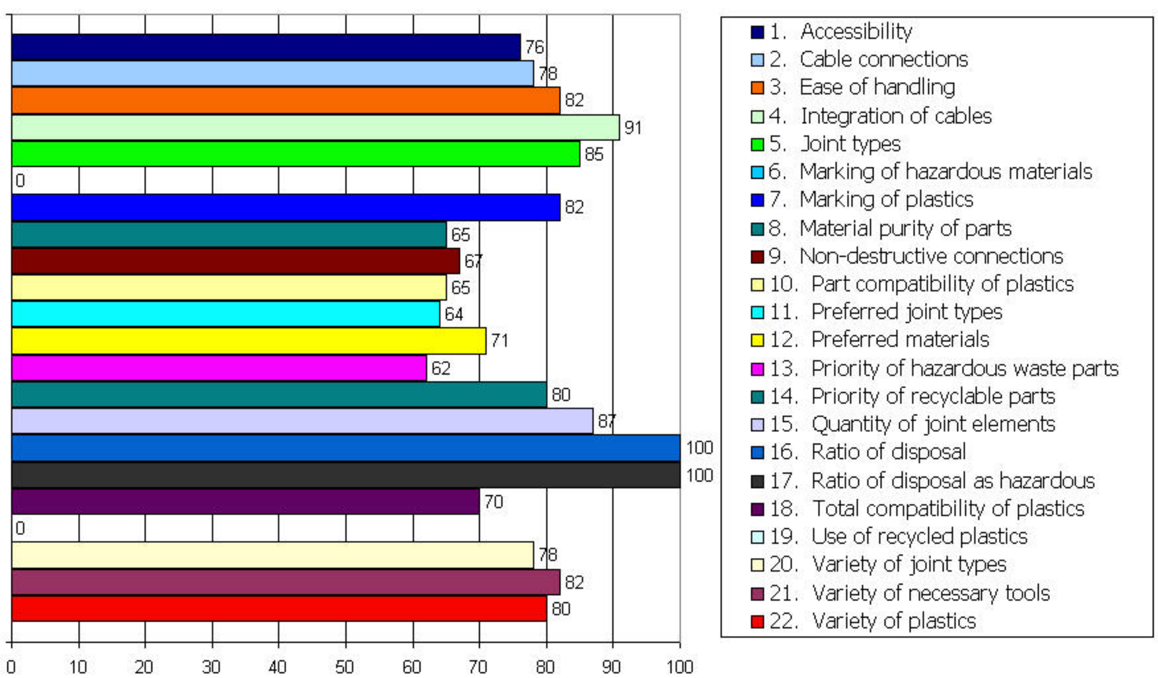


Figure 5-20: The wheel mouse: report recycling orientation.
[Report] – model > (Report Recycling Orientation).

These data could be used for improving the product recycling-oriented performance, by investigating on weak points of each category and searching for potential improvement. From the software calculation, the average score of recycling-orientation of product design of the wheel mouse = 71.64. The score at "(6) Marking of hazardous materials," and “(19) Use of recycled plastics” are equal to “0,” see the figure. This is because from the product profiles and the investigation (disassembling analysis), there are no marking of hazardous materials and no information on the use of recycled plastics.

Usually, products designers (users) have put in a lot of effort in improving product functions, mechanical design, cost & benefit analysis, technical possibility to produce, in addition to meeting legislative requirement of the company. However, sufficient consideration is not given to the products' EOL management. This software helps to visualize and improve the EOL management (recycling, treatment) of the products. The designer team should consist of people with expertise in different fields (a multi-disciplinary) in order to get broader ideas and view points for better results/alternatives for product design, and prototyping.

This dissertation strives to construct algorithms, and build the system for determining the recycling-orientation of product at design stage. Issues of product design: product recycling-oriented optimization is beyond the scope of this dissertation and need to be obtained from other sources (various), however hints are provided in **Section** 4.8.7 (recycling-oriented product design), **Section 2.4.2** (overview of product design), and **Section 2.4.3** (product development as a whole).

5.4.3.5 Report Performance Indicator

The [Product Performance Indicator] *Graph* can be obtained by clicking *View Graph* button. The meaning of the product performance indicator and their categories has been described in **Section 4.11.4**.

The wheel mouse comprises: Plastic {ABS} 35%, Metal + Epoxy Coated 25%, Insulated Copper Wires 25%, PCB (Printed Circuit Board) 11%, Plastic {Unidentified} with IC 4% (see also **Figure 5-5**), all of these materials have the market for sale, therefore the recycling rate of the product = 100% (see **Appendix**, **Table A-28**). The recycling-orientation of product design which obtained from the previous section = 71.64. Hence, the performance indicator can be calculated. The wheel mouse has the Performance Indicator (PI) as following:

$$PI = [RR \times RO]^{1/2}$$
$$= (100.00 \times 71.64)^{1/2}$$
$$= (7{,}163.64)^{1/2}$$
$$\therefore PI = 84.64$$

Additionally, the wheel mouse has been categorized in category 3: "IT and telecommunications equipment," under the WEEE directive, Annex IB (Directive 2002/96/EC, 2003). It is worth nothing that the wheel mouse in compliance with the directive that its recovery rate be greater than 75 % by an average weight per appliance, and its reuse and recycling be greater than 65 % by an average weight per appliance.

The Performance Indicator of the product can be obtained by plotting the RR (100.00), and RO (71.64) into the performance indicator chart (see **Figure 5-21**).

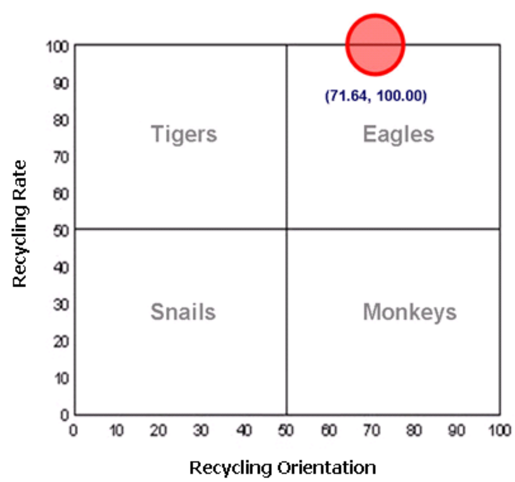


Figure 5-21: The wheel mouse: report performance indicator.
[Report] – model > [Report Performance Indicator].

From the figure, the plotted RR and RO eventually depicted that the product is categorized as "Eagles." The Eagles refers to products, which have recycling rate and recycling-orientation greater than 50. They represent the state-of-the-art and standards of green products.

Moreover, when we consider economic issues, the recycling indicator can be obtained as follows. The initial cost of mouse = 5.00 € (first hand from dealers), and the recycling profit = 0.04 €, therefore RV = 0.04 ÷ 5.00 x 100 ∴ RV = 0.80. Hence, the recycling indicator can be calculated. The wheel mouse has Recycling Indicator (RI) as following:

$$\begin{aligned} RI &= [RR \times RO \times RV]^{1/3} \\ &= (100.00 \times 71.64 \times 0.80)^{1/3} \\ &= (5{,}731.20)^{1/3} \\ \therefore RI &= 17.89 \\ \text{Product Category} &= \text{Eagles, with RV} = 17.89 \end{aligned}$$

The Recycling Indicator (RI) of the wheel mouse can then be plotted (see **Figure 5-22**).

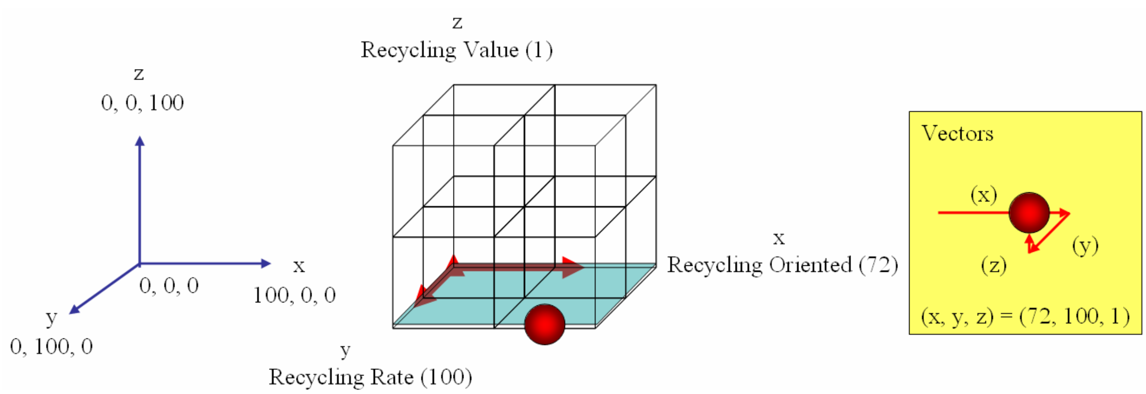


Figure 5-22: The wheel mouse: recycling indicator.

These obtained values i.e., RR, RO, RV, PI, RI, and the product category, can be used as a basis for further benchmarking with other product models. Even though, the wheel mouse has EOL benefit, 0.04 €/product; in reality, this benefit is too small for recyclers to operate. This example only gives an idea of how the ReOAT procedure works. The understanding of the ReOAT's procedure will help for further use and interpretation of the results. For other business solutions and service, there are other factors that are involved e.g., related research (**Chapter 2**), and research software (**Chapter 3**), the users must incorporate other knowledge and information together.

In the procedure, errors might arise from (1) wrong (imprecision) calibration, (2) misreading measurement while dismantling, (3) modeling incorrect product structure, (4) typing mistake (typographical error) into the software, and (5) using outdated information, which should be avoided. Moreover, when using these results for comparing different products models, the results obtained should be compared with those from the same time period. Technologies develop fast, politics, economics situations and other factors change with time. The demand and supply of the market, and customers needs are some of the most important factors that influence on products development directions.

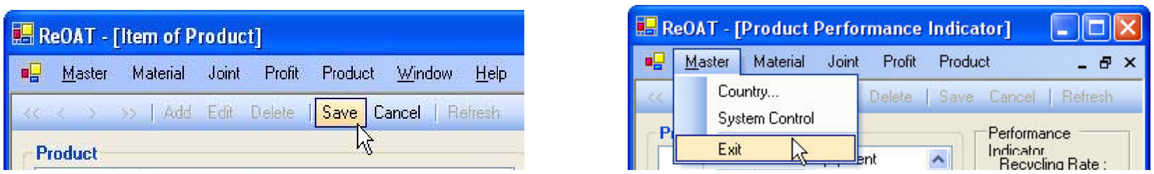
Usually, recyclers are interested in recycling materials/scraps in large quantities (tons of products e.g., EOL cars) so that they can operate with the advantage of economy of large quantity by scale. Recyclers (dismantling companies), would like to get maximum profit per operation time. For example, assuming there were three kinds of products that needed to be recycled and the time required for dismantling the three different kinds of product are equal. The EOL benefits of the three products are: (1) five tons of EOL dishwashing machines, which gives 75 € benefit; (2) five tons of EOL lawnmowers, which gives 90 € benefit; and (3) five tons of wheel mice, which give 30 € benefit. The recycler can carry out only one kind of product per day, because of lack of personnel and operation. With these constraints and limitations, the recycler will definitely select the five tons of EOL lawnmowers, all things are being equal. Sometimes, some EOL products give high profit, in the case that the products are rare, unique, and still on demand.

Nowadays white goods, appliances, IT products, obviously are designed to be slimmer (e.g., LCD TV), lighter (e.g., notebook), more efficient (e.g., energy saving lamp), and of course greener, which consume less energy during operation or transport. The ideal product, preferably should have high recycling rate, high recycling-orientation, and high recycling value, attributes that influence product recycling. The ideal product should also have low human health and environmental impacts during the entire product life-span, from “cradle-to-grave.” LCA is a tool that could be used for quantifying the product’s environmental impacts. Energy using products are designed to consume less energy, tool such as eco-design could be helpful in this respect to reduce the use of energy, water, and auxiliary materials during operation. Innovations, technologies, and material researches are ongoing with the goal of meeting human needs and aspirations with conservation of natural resources and minimization of environmental burdens.

The environmental technological aspects such as nanotechnologies, and biotechnologies, are open the windows of hope for the future for the attainment of SD. It is predicted that these technologies would play an important role to answer the question of, how to produce products with less (or zero) emissions/wastes, with the enhancement of products efficiency as well as gives more product choices for consumers. New products and technologies or services may change consumption behaviors and ways of life of consumers completely. For example, in the context of microelectronics (computer chips), the number of transistors in microprocessor (CPU) has dramatically increased in the past four decades. The size of transistors is much smaller with less energy consumption and less heat production. The first microprocessor 4004 was introduced in 1971, with 2,250 transistors; in 2002 Pentium 4 has 42,000,000 transistors (Intel, 2005). The European Competitiveness Report (EC, 2000), prepared by the European Commission, notes: “According to the so-called Moore’s law, microchip capabilities double every 18 months.” The report of ITRS, notes that within the next 10-15 years “most of the known technological capabilities will approach or would have reached their limits” (ITRS, 2001). This is probably true for chips making. Trend in the past decade indicates that the increasing number of transistors in microchip has slowed down. Nevertheless, the power of the computer continue to rise, because of several factors e.g., the capacity of memories (RAM, cache memory) and storages (hard disk drive) that have improved considerably. The same applied to data transmission rate between components (BUS). This tells us that for product improvement (e.g., computer), not only the core elements (e.g., CPU) need taking into account, but also other indispensable components (e.g., Ram, cache memory, BUS) are important for increasing the product’s efficiency as a whole).

5.4.3.6 Project Save and Exit

When modifications are make to the database, the software will automatically *Save* changes, in some case, however, users may need to trigger the *Save* command, e.g. after adding new part of the product model which has more than one active windows, each window has to be saved manually (see **Figure 5-23a**). To exit the software (see **Figure 5-23b**), at the command menu: [Master] – model > (Exit).



(a) (b)

Figure 5-23: (a) save change – manually; (b) exit the software.

Chapter 6

Conclusions

A vast variety of product categories, designs and functions make it difficult to evaluate the recycling orientation of products precisely because there are numerous details associated with individual product, which cannot be regulated by one single standard. Different countries, different companies or group of companies have different product standards. Though the standards of one company can be used for benchmarking recycling orientation of different products, the corresponding results obtained can merely be used for internal purposes and cannot apply to the products of other companies. The standards and regulations available include, third-party certification label, ISO standards, regional and national laws, integrated product policy, extended product responsibilities, and product stewardship that stipulate product design concepts and guidelines for producers with regard to material consumption, energy use, ease of disassembly, ease of recycling, return and collection systems, product life-cycle, human health and environmental concerns, which can be used for outlining product development plan. There is however, no concrete international standard as a holistic approach to integrating and rating the recycling-orientation of products.

This dissertation tends to tackle this problem, by investigating the need for rating the recycling-orientation of products, and developing a new solution tool, ReOAT. Issues concerned with making ReOAT are related to the selection of the starting points for variables, choices of initial barrier parameters, and subsequent adjustment of the barrier parameters according to progress. Theory has little to say about such matters, but poor choices and designs can lead to poor performance. Given the variety and difficulty of rating/assessing different type of products and finding optimal results, it is unlikely that a single best algorithm will emerge. Much needs to be done to improve the efficiency and robustness of the algorithm.

6.1 Summary of Contributions

This dissertation makes a number of key contributions:

- **Provide databases as a basis for calculating the recyclability of product.** Various databases e.g., material, disassembly tool, disassembly time, disassembly cost, and recycling benefit have been synthesized into the concept of this dissertation. The completed data is fully integrated in the software ReOAT.
- **Derive recycling orientation criteria and building of functions from various sources.** The recycling orientation criteria of product and the functional components of the software are partially derived from related researches and related softwares, which are described in Chapter 2, and Chapter 3. The integration of these functionalities has been made in this dissertation, and this enables the building and execution of any product model by means of the software ReOAT. As a result the recyclability of product can be calculated.
- **Offer an alternative to complex architectures.** ReOAT is a shift of focus from a complex packaging of all features into a single set to keeping things simple. The ReOAT core provides basic structure, enabling software users to define and execute product model. Its procedure, execution, and modeling encapsulate the design decisions on product description, and product improvement. This yields a simple foundation that is easy to understand, customize, and integrate with other systems, and applications.
- **Offer an extendable property for advanced features and databases.** ReOAT allows software developers to add features typical of systems by adding components to the core. This characteristic enables the architecture to grow and accommodate new functionalities.
- **Prove that the architecture can be built and sustainable.** ReOAT proves that this type of architecture can be built and that it can implement commands with different requirements. The eight object-oriented models described in Chapter 4 show how to present the abstractions provided by the ReOAT architecture with

objects. The framework models implements the ReOAT components with e.g., Visual Basic .NET programming language, Crystal Report, and Microsoft Access. The ability to add features by adding components provides sustainable alternatives for users who need a customizable solution tool.

In addition to the key contributions discussed above, the dissertation provides the following supplementary contributions:

- **Permit developers to add new components.** Unlike traditional architectures, ReOAT allows software developers to add new features by adding new components. ReOAT offers a road map for customizing the existing structure and building additional components, which are the main advantages of using components. It employed an object-oriented technology, which provides a complete architectural style for software management that can extend and improve limited range of data types and computational features in the future.
- **Teach users how to use the architecture.** The case problem described in Chapter 5 demonstrates how to solve the problem by means of ReOAT. Besides providing a qualitative and quantitative evaluation, it also shows how to use ReOAT to virtually build a product model. The case problem serves as a starting point for implementing ReOAT with a variety of requirements. The ReOAT architecture allows software users/designers to choose, construct and model products they investigate. It enables them to investigate and address recycling orientation and relevant issues of existing and new products. ReOAT also permits prototyping models through programming techniques flexible for adding, editing, and deleting specific data components. The software provides communication stages between users and the software, each stage gradually introduces more information to subsequent stages. These characteristics and features represent a significant departure from traditional architectures.
- **Provide example of documented dismantling analysis.** Recycling literature contains very few examples of dismantling analysis. Obtaining examples is

usually hard since companies don't want to reveal their internal composition, joining techniques, and material of their products. The example helps researchers to test ideas, evaluate solutions, and choose between alternatives. The case problem discussed in Chapter 5 provides a comprehensive dismantling analysis with different rationale clarifications.

- **Contribute to recycling-oriented society for sustainable development.** By means of recycling materials, the use of raw materials can be reduced and thus prolong the material cycles, and their utilizations. ReOAT is considered as one of the recycling-oriented product design tools that help to enhance the recyclability of products.

6.2 Future Work

ReOAT data acquisition process is manageable by hand, for instance the case problem, presented in Chapter 5, but this could become cumbersome when working with larger and complex model. The system still needs to be tested with larger size projects to ascertain the significance of this challenge. Additional database may required. Different databases use different dialects or extensions of standard SQL, therefore a query accepted by one server may be considered malformed by another; it is recommended that type of incoming database should be compatible or tuneable with the earlier database. An ideal programming system that is outstanding in performances would need to be supported by a suite of tools for program editing, data modeling, data analysis and reporting. With regard to the improvement of the core system, the following features are concerned:

- **Scripting**. At each step of adding a new feature or modifying existed features, the application record should maintain the documentation of the implementation. This makes it easy for the programmer to roll back implementation decisions when: looking for better solutions; exporting the software to a different architecture; or amending a component for a different usage.

- **User Interface.** Application of complex and sophisticate programming steps loaded with a number of data types would need a productive user interface. The interface must be able to protect the users from the complexity of the system by eliminating non-necessary details that are not currently important. It must also support rather than hinder the users.
- **Support Tool.** There are many possibilities for incorporated useful and powerful tool suite into the software; the programmer would need pertinent support tools to provide guidance and perform desired changes correctly. These decision stages require insight and aspiration; certain tool must be directed by the programmer rather than be fully automated. At least, the support software would be an interactive editor that applies transformations to the program text. It should verify at each step that the transformation being applied is valid, and record any tie conditions or assumptions made.

A tool should provide alternative pathways for further development. Often the programmer will not know which alternative is the best to proceed with. It is recommended be carried out with that experiment a few alternatives in parallel, in order to identify most optimal alternatives that are available.

6.3 Closing Statement

This dissertation proposes the ReOAT architecture as a better way of implementing database management within object-oriented applications. Essentially, this dissertation demonstrates that with the ReOAT architecture, software users can model and rate products, regardless of type of products. The approach described in this dissertation is expected to have broad applications and benefits in product development.

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Appendix A

ReOAT Data Standard

A.1 Recycling-Oriented Product Design Category

Table A-1: Recycling-oriented product design category.

1. Accessibility	12. Preferred materials
2. Ease of handling	13. Priority of hazardous waste parts
3. Cable connections	14. Priority of recyclable parts
4. Integration of cables	15. Quantity of joint elements
5. Joint types	16. Ratio of disposal
6. Marking of hazardous materials	17. Ratio of disposal as hazardous
7. Marking of plastics	18. Total compatibility of plastics
8. Material purity of parts	19. Use of recycled plastics
9. Non-destructive connections	20. Variety of joint types
10. Part compatibility of plastics	21. Variety of necessary tools
11. Preferred joint types	22. Variety of plastics

A.2 Recycling-Oriented Product Design Score

Table A-2: Accessibility score.

Degree of accessibility = 4 *excellent*	Degree of accessibility = 3 *fair*	Degree of accessibility = 2 *poor*	Degree of accessibility = 1 *re-design*
100	50	5	0

Table A-3: Cable connections score.

Number of cable between parts = 1 100	Number of cable between parts = 2 90	Number of cable between parts =3 75
Number of cable between parts = 4 45	Number of cable between parts = 5 0	Number of cable between parts > 5 0

Table A-4: Ease of handling score.

Box 100	Flat rectangular 80	Rectangular rod 25
Cylinder 75	Flat cylinder 50	Round rod 15

Table A-5: Integration of cables score.

Assembled connector 100	Quick connect lug (terminals) 75	Fork terminal (lug) 50	Terminal (lug) 50
Tinned wires 50	Ring terminal (lug) 40	Leg 25	

Table A-6: Number of joint elements score.

Number of Joint Elements = 1 *excellent*	Number of Joint Elements = 2 *fair*	Number of Joint Elements = 3 *poor*	Number of Joint Elements > 3 *re-design*
100	50	5	0

Table A-7: Marking of hazardous material score.

Detect marking of hazardous materials = “Yes” *excellent*	Detect marking of hazardous materials = “No” *re-design*
100	0

Table A-8: Marking of plastics score.

Detect marking of plastics = “Yes” *excellent*	Detect marking of plastics = “No” *re-design*
100	0

Table A-9: Material purity of parts score.

Material purity of parts, Number of material used = 1 *excellent*	Material purity of parts, Number of material used > 1 *Re-design*
100	0

Table A-10: Non-destructive connections score.

Parts are connected by non-destructive connections = “Yes” *excellent*	Parts are connected by non-destructive connections = “No” *re-design*
100	0

Table A-11: Part compatibility of plastics score.

Degree of plastics compatibility = 2 *excellent*	Degree of plastics compatibility = 1 *fair*	Degree of plastics compatibility = 0 *re-design*
100	50	0

Table A-12: Preferred joint types score.

Degree of separable = 3 *excellent*	Degree of Separable = 2 *fair*	Degree of separable = 1 *poor*	Degree of separable = 0 *re-design*
100	50	5	0

Table A-13: Preferred materials score.

Degree of recyclability = 3 *excellent*	Degree of recyclability = 2 *fair*	Degree of recyclability = 1 *poor*	Degree of recyclability = 0 *re-design*
100	50	5	0

Table A-14: Priority of hazardous waste score.

Number of items that have to be removed before reaching the hazardous part = 1 *excellent*	Number of items that have to be removed before reaching the hazardous part = 2 *fair*	Number of items that have to be removed before reaching the hazardous part = 3 *poor*	Number of items that have to be removed before reaching the hazardous part = 4 *re-design*
100	50	5	0

Table A-15: Priority of recyclable parts score.

Number of items that have to be removed before reaching the recyclable/valuable part = 1 *excellent*	Number of items that have to be removed before reaching the recyclable/valuable part = 2 *fair*	Number of items that have to be removed before reaching the recyclable/valuable part = 3 *poor*	Number of items that have to be removed before reaching the recyclable/valuable part = 4 *re-design*
100	50	5	0

Table A-16: Quantity of joint elements score.

Quantity of joint elements = 1 *excellent*	Quantity of joint elements = 2 *fair*	Quantity of joint elements = 3 *poor*	Quantity of joint elements = 4 *re-design*
100	50	5	0

Table A-17: Ratio of disposal score (by weight).

Ratio of disposal = 0.00-0.25 *excellent*	Ratio of disposal = 0.26-0.50 *fair*	Ratio of disposal = 0.51-0.75 *poor*	Ratio of disposal = 0.76-1.00 *re-design*
100	50	5	0

Table A-18: Disposal as hazardous ratio score (by weight).

Ratio of disposal as hazardous = 0.00-0.25 *excellent*	Ratio of disposal as hazardous = 0.26-0.50 *fair*	Ratio of disposal as hazardous = 0.51-0.75 *poor*	Ratio of disposal as hazardous = 0.76-1.00 *re-design*
100	50	5	0

Table A-19: Total compatibility of plastics score (by weight).

Degree of total compatibility of plastics = 2 *Excellent*	Degree of total compatibility of plastics = 1 *fair*	Degree of total compatibility of plastics = 0 *re-design*
100	50	0

Table A-20: Recycled plastics used share score.

Ratio of recycle plastics used = 0.76-1.00 *excellent*	Ratio of recycle plastics used = 0.51-0.75 *fair*	Ratio of recycle plastics used = 0.26-0.50 *poor*	Ratio of recycle plastics used = 0.00-0.25 *re-design*
100	50	5	0

Table A-21: Variety of joint types score.

Number of joint types = 1, 2, 3 *excellent*	Number of joint types = 4, 5 *fair*	Number of joint types > 5 *re-design*
100	50	0

Table A-22: Variety of necessary tools score.

Number of variety necessary tools = 1, 2, 3 *excellent*	Number of variety necessary tools = 4, 5 *fair*	Number of variety necessary tools > 5 *re-design*
100	50	0

Table A-23: Variety of plastics score.

Number of plastics types = 1, 2, 3, 4, 5 *excellent*	Number of plastics types = 6, 7, 8, 9, 10 *fair*	Number of plastics types = 11, 12, 13, 14, 15 *poor*	Number of plastics types > 15 *re-design*
100	30	5	0

A.3 Recycling-Oriented Product Design: Additional Data

Table A-24: Thermoplastics compatibility (source: Branson Ultrasonics Corp., Danbury, CT).

	ABS	ABS/polycarbonate alloy (Cycoloy 800)	Acrylic	Acrylic multipolymer	Butadiene–styrene	Phenylene-oxide based resins (Noryl)	Polyamide-imide (Torlon)	Polyarylate	Polycarbonate	Polyetherimide	Polyethersulfone	Polystyrene (general purpose)	Polystyrene (rubber modified)	Polysulfone	PVC (rigid)	SAN-NAS-ASA	Semicrystalline Resins
Amorphous Resins																	
ABS	■	■	■	○											○	○	
ABS/polycarbonate alloy (Cycoloy 800)	■	■	○						■								
Acrylic	■	○	■	○		○			○							○	
Acrylic multipolymer	○		○	■								○				○	
Butadiene–styrene					■							○					
Phenylene-oxide based resins (Noryl)			○			■			○			■				○	
Polyamide-imide (Torlon)							■										
Polyarylate								■									
Polycarbonate		■	○			○			■	○				○			
Polyetherimide									○	■							
Polyethersulfone											■						
Polystyrene (general purpose)				○	○	■						■				○	
Polystyrene (rubber modified)													■				
Polysulfone									○					■			
PVC (rigid)	○														■		
SAN-NAS-ASA	○		○	○		○						○				■	
Semicrystalline Resins																	

Solid squares, compatibility; open circles, compatibility in some cases (usually).

Table A-25: Degree of separable.

DS	Joint Type	Specification	DS	Joint Type	Specification
3	Embody/contact	Together	2	Press in	Clamping joint
3	Embody/contact	Insert	2	Twisted up	-
3	Sliding joint	-	1	Shape joint	Twisted shape lock
3	Snap fastener	Type A	1	Shape joint	Folded seam connection
3	Snap fastener	Type B	1	Shape joint	Edged connection
3	Snap fastener	Type C	1	Shape joint	Bent shape lock
3	Snap fastener	Type D	1	Distort	-
3	Snap fastener	Type E	0	Shape joint	Riveted connection
2	Hang up	Spring	0	Shape joint	Pivot riveted connection
2	Hang up	Gravity	0	Press in	Nail
2	Wire connection	Single/integrated cable	0	Glued joint	Glued pipes
2	Screw connection	Wing screw	0	Glued joint	Flat surface
2	Screw connection	Slotted screw	0	Press in	Compression joint
2	Screw connection	Philips screw	0	Soldered joint	-
2	Screw connection	Hexagon socket screw	0	Extrusion coat	-
2	Screw connection	Hexagon slotted screw	0	Welding	Spot welded plastic
2	Screw connection	Hexagon phillips	0	Welding	Welded plastic
2	Screw connection	Hexagon head screw	0	Welding	Welded metal
2	Wire connection	Flat cable			

DS = Degree of Separable: 3 = *excellent*; 2 = *good*; 1 = *poor* ; 0 = *re-design*

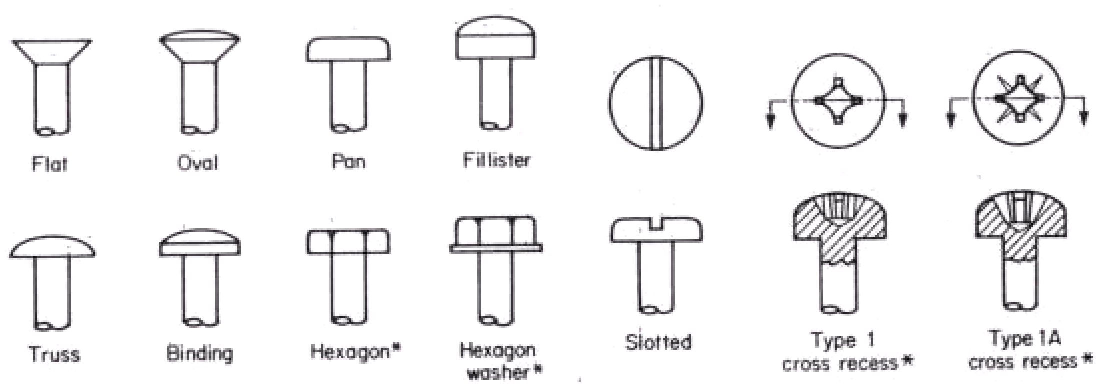


Figure A-1: Type of screws (source: Bralla, 1986).

Table A-26: Joint types.

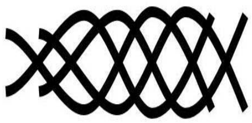
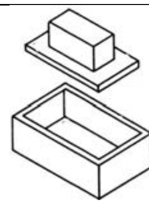
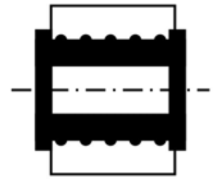
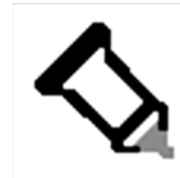
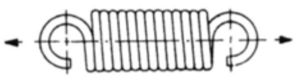
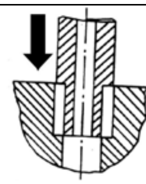
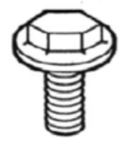
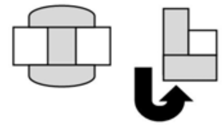
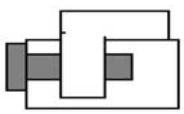
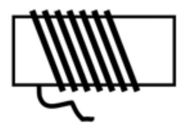
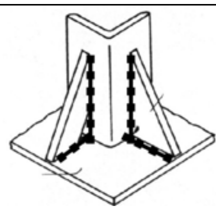
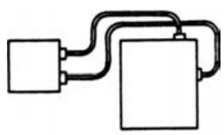
 Distort	 Embody/contact	 Extrusion coat	 Glued joint
 Hang up	 Press in	 Screw connection	 Shape joint
 Sliding joint	 Snap fastener	 Soldered joint	 Twisted up
 Welding	 Wire connection		

Table A-27: Variety of necessary tools.

1. Bolt cutter	10. Screw breaker against hexagon head screws
2. Chisel	11. Screw breaker against hexagon socket screws
3. Chisel with hammer	12. Screw breaker against slotted head screws
4. Diagonal cutting nipper	13. Screwdriver against cross-recessed head screws
5. Hexagon socket screw key	14. Screwdriver against slotted head screws
6. Mandrill with hammer	15. Shell bit
7. Pliers	16. Soldering copper
8. Saw	17. Tooless
9. Screw breaker against cross-recessed head screws	18. Wrench

A.4 ReOAT Disassembly Time: Data Sheet

Table A-28: Disassembly time.

No.	Joint Type	Joint Type Specification	Disassembly Tool	Direction	Dis-assembly Time
1	Distort	#	Diagonal cutting nipper	East	4.89
2	Distort	#	Diagonal cutting nipper	North	4.95
3	Distort	#	Diagonal cutting nipper	South	5.13
4	Distort	#	Diagonal cutting nipper	Vertical	4.80
5	Distort	#	Diagonal cutting nipper	West	5.05
6	Distort	#	Pliers	East	5.34
7	Distort	#	Pliers	North	5.40
8	Distort	#	Pliers	South	5.53
9	Distort	#	Pliers	Vertical	5.26
10	Distort	#	Pliers	West	5.46
11	Embody/contact	Insert	Tooless	East	0.99
12	Embody/contact	Insert	Tooless	North	0.99
13	Embody/contact	Insert	Tooless	South	0.99
14	Embody/contact	Insert	Tooless	Vertical	0.99
15	Embody/contact	Insert	Tooless	West	0.99
16	Embody/contact	Together	Tooless	East	0.99
17	Embody/contact	Together	Tooless	North	0.99
18	Embody/contact	Together	Tooless	South	0.99
19	Embody/contact	Together	Tooless	Vertical	0.99
20	Embody/contact	Together	Tooless	West	0.99
21	Extrusion coat	#	Chisel	East	4.91
22	Extrusion coat	#	Chisel	North	4.97
23	Extrusion coat	#	Chisel	South	5.15
24	Extrusion coat	#	Chisel	Vertical	4.83
25	Extrusion coat	#	Chisel	West	5.05
26	Extrusion coat	#	Chisel with hammer	East	2.72
27	Extrusion coat	#	Chisel with hammer	North	2.78
28	Extrusion coat	#	Chisel with hammer	South	2.95

29	Extrusion coat	#	Chisel with hammer	Vertical	2.64
30	Extrusion coat	#	Chisel with hammer	West	2.85
31	Glued joint	Flat surface	Chisel	East	3.13
32	Glued joint	Flat surface	Chisel	North	3.18
33	Glued joint	Flat surface	Chisel	South	3.36
34	Glued joint	Flat surface	Chisel	Vertical	3.05
35	Glued joint	Flat surface	Chisel	West	3.26
36	Glued joint	Flat surface	Chisel with hammer	East	3.13
37	Glued joint	Flat surface	Chisel with hammer	North	3.18
38	Glued joint	Flat surface	Chisel with hammer	South	3.36
39	Glued joint	Flat surface	Chisel with hammer	Vertical	3.05
40	Glued joint	Flat surface	Chisel with hammer	West	3.26
41	Glued joint	Glued pipes	Saw	East	3.55
42	Glued joint	Glued pipes	Saw	North	3.61
43	Glued joint	Glued pipes	Saw	South	3.79
44	Glued joint	Glued pipes	Saw	Vertical	3.48
45	Glued joint	Glued pipes	Saw	West	3.69
46	Hang up	Gravity	Tooless	East	0.99
47	Hang up	Gravity	Tooless	North	0.99
48	Hang up	Gravity	Tooless	South	0.99
49	Hang up	Gravity	Tooless	Vertical	0.99
50	Hang up	Gravity	Tooless	West	0.99
51	Hang up	Spring	Diagonal cutting nipper	East	2.19
52	Hang up	Spring	Diagonal cutting nipper	North	2.25
53	Hang up	Spring	Diagonal cutting nipper	South	2.39
54	Hang up	Spring	Diagonal cutting nipper	Vertical	2.12
55	Hang up	Spring	Diagonal cutting nipper	West	2.31
56	Press in	Clamping joint	Pliers	East	3.15
57	Press in	Clamping joint	Pliers	North	3.20
58	Press in	Clamping joint	Pliers	South	3.34
59	Press in	Clamping joint	Pliers	Vertical	3.07
60	Press in	Clamping joint	Pliers	West	3.26
61	Press in	Compression joint	Mandrill with hammer	East	4.27
62	Press in	Compression joint	Mandrill with hammer	North	4.33
63	Press in	Compression joint	Mandrill with hammer	South	4.62

64	Press in	Compression joint	Mandrill with hammer	Vertical	4.19
65	Press in	Compression joint	Mandrill with hammer	West	4.43
66	Press in	Nail	Mandrill with hammer	East	2.68
67	Press in	Nail	Mandrill with hammer	North	2.47
68	Press in	Nail	Mandrill with hammer	South	3.03
69	Press in	Nail	Mandrill with hammer	Vertical	2.60
70	Press in	Nail	Mandrill with hammer	West	2.54
71	Screw connection	Hexagon with phillips	Screw breaker against cross-recessed head screws	East	4.74
72	Screw connection	Hexagon with phillips	Screw breaker against cross-recessed head screws	North	4.72
73	Screw connection	Hexagon with phillips	Screw breaker against cross-recessed head screws	South	4.82
74	Screw connection	Hexagon with phillips	Screw breaker against cross-recessed head screws	Vertical	4.74
75	Screw connection	Hexagon with phillips	Screw breaker against cross-recessed head screws	West	4.72
76	Screw connection	Hexagon with phillips	Screw breaker against hexagon head screws	East	4.74
77	Screw connection	Hexagon with phillips	Screw breaker against hexagon head screws	North	4.72
78	Screw connection	Hexagon with phillips	Screw breaker against hexagon head screws	South	4.82
79	Screw connection	Hexagon with phillips	Screw breaker against hexagon head screws	Vertical	4.74
80	Screw connection	Hexagon with phillips	Screw breaker against hexagon head screws	West	4.72
81	Screw connection	Hexagon with phillips	Screwdriver against cross-recessed head screws	East	4.82
82	Screw connection	Hexagon with phillips	Screwdriver against cross-recessed head screws	North	4.80
83	Screw connection	Hexagon with phillips	Screwdriver against cross-recessed head screws	South	4.76
84	Screw connection	Hexagon with phillips	Screwdriver against cross-recessed head screws	Vertical	4.83
85	Screw connection	Hexagon with phillips	Screwdriver against cross-recessed head screws	West	4.78
86	Screw connection	Hexagon with phillips	Wrench	East	4.52
87	Screw connection	Hexagon with phillips	Wrench	North	4.50
88	Screw connection	Hexagon with phillips	Wrench	South	4.47
89	Screw connection	Hexagon with phillips	Wrench	Vertical	4.54
90	Screw connection	Hexagon with phillips	Wrench	West	4.49
91	Screw connection	Hexagon with Slotted	Screw breaker against hexagon head screws	East	4.74
92	Screw connection	Hexagon with Slotted	Screw breaker against hexagon head screws	North	4.72
93	Screw connection	Hexagon with Slotted	Screw breaker against hexagon head screws	South	4.82
94	Screw connection	Hexagon with Slotted	Screw breaker against hexagon head screws	Vertical	4.74

95	Screw connection	Hexagon with Slotted	Screw breaker against hexagon head screws	West	4.72
96	Screw connection	Hexagon with Slotted	Screw breaker against slotted head screws	East	4.74
97	Screw connection	Hexagon with Slotted	Screw breaker against slotted head screws	North	4.72
98	Screw connection	Hexagon with Slotted	Screw breaker against slotted head screws	South	4.82
99	Screw connection	Hexagon with Slotted	Screw breaker against slotted head screws	Vertical	4.74
100	Screw connection	Hexagon with Slotted	Screw breaker against slotted head screws	West	4.72
101	Screw connection	Hexagon with Slotted	Screwdriver against slotted head screws	East	4.82
102	Screw connection	Hexagon with Slotted	Screwdriver against slotted head screws	North	4.80
103	Screw connection	Hexagon with Slotted	Screwdriver against slotted head screws	South	4.76
104	Screw connection	Hexagon with Slotted	Screwdriver against slotted head screws	Vertical	4.83
105	Screw connection	Hexagon with Slotted	Screwdriver against slotted head screws	West	4.78
106	Screw connection	Hexagon with Slotted	Wrench	East	4.52
107	Screw connection	Hexagon with Slotted	Wrench	North	4.50
108	Screw connection	Hexagon with Slotted	Wrench	South	4.47
109	Screw connection	Hexagon with Slotted	Wrench	Vertical	4.54
110	Screw connection	Hexagon with Slotted	Wrench	West	4.49
111	Screw connection	Hexagon head screw	Screw breaker against hexagon head screws	East	4.74
112	Screw connection	Hexagon head screw	Screw breaker against hexagon head screws	North	4.72
113	Screw connection	Hexagon head screw	Screw breaker against hexagon head screws	South	4.82
114	Screw connection	Hexagon head screw	Screw breaker against hexagon head screws	Vertical	4.74
115	Screw connection	Hexagon head screw	Screw breaker against hexagon head screws	West	4.72
116	Screw connection	Hexagon head screw	Wrench	East	4.52
117	Screw connection	Hexagon head screw	Wrench	North	4.50
118	Screw connection	Hexagon head screw	Wrench	South	4.47
119	Screw connection	Hexagon head screw	Wrench	Vertical	4.54
120	Screw connection	Hexagon head screw	Wrench	West	4.49
121	Screw connection	Hexagon socket screw	Hexagon socket screw key	East	4.52
122	Screw connection	Hexagon socket screw	Hexagon socket screw key	North	4.50
123	Screw connection	Hexagon socket screw	Hexagon socket screw key	South	4.47
124	Screw connection	Hexagon socket screw	Hexagon socket screw key	Vertical	4.54
125	Screw connection	Hexagon socket screw	Hexagon socket screw key	West	4.49

126	Screw connection	Hexagon socket screw	Screw breaker against hexagon head screws	East	4.74
127	Screw connection	Hexagon socket screw	Screw breaker against hexagon head screws	North	4.72
128	Screw connection	Hexagon socket screw	Screw breaker against hexagon head screws	South	4.82
129	Screw connection	Hexagon socket screw	Screw breaker against hexagon head screws	Vertical	4.74
130	Screw connection	Hexagon socket screw	Screw breaker against hexagon head screws	West	4.72
131	Screw connection	Hexagon socket screw	Screw breaker against hexagon socket screws	East	4.74
132	Screw connection	Hexagon socket screw	Screw breaker against hexagon socket screws	North	4.72
133	Screw connection	Hexagon socket screw	Screw breaker against hexagon socket screws	South	4.82
134	Screw connection	Hexagon socket screw	Screw breaker against hexagon socket screws	Vertical	4.74
135	Screw connection	Hexagon socket screw	Screw breaker against hexagon socket screws	West	4.72
136	Screw connection	Hexagon socket screw	Wrench	East	4.52
137	Screw connection	Hexagon socket screw	Wrench	North	4.50
138	Screw connection	Hexagon socket screw	Wrench	South	4.47
139	Screw connection	Hexagon socket screw	Wrench	Vertical	4.54
140	Screw connection	Hexagon socket screw	Wrench	West	4.49
141	Screw connection	phillips screw	Screw breaker against cross-recessed head screws	East	4.74
142	Screw connection	phillips screw	Screw breaker against cross-recessed head screws	North	4.72
143	Screw connection	phillips screw	Screw breaker against cross-recessed head screws	South	4.82
144	Screw connection	phillips screw	Screw breaker against cross-recessed head screws	Vertical	4.74
145	Screw connection	phillips screw	Screw breaker against cross-recessed head screws	West	4.72
146	Screw connection	phillips screw	Screwdriver against cross-recessed head screws	East	4.82
147	Screw connection	phillips screw	Screwdriver against cross-recessed head screws	North	4.80
148	Screw connection	phillips screw	Screwdriver against cross-recessed head screws	South	4.76
149	Screw connection	phillips screw	Screwdriver against cross-recessed head screws	Vertical	4.83
150	Screw connection	phillips screw	Screwdriver against cross-recessed head screws	West	4.78
151	Screw connection	phillips screw	Shell bit	East	4.29
152	Screw connection	phillips screw	Shell bit	North	4.35
153	Screw connection	phillips screw	Shell bit	South	4.52
154	Screw connection	phillips screw	Shell bit	Vertical	4.21
155	Screw connection	phillips screw	Shell bit	West	4.39

156	Screw connection	Slotted screw	Screw breaker against slotted head screws	East	4.74
157	Screw connection	Slotted screw	Screw breaker against slotted head screws	North	4.72
158	Screw connection	Slotted screw	Screw breaker against slotted head screws	South	4.82
159	Screw connection	Slotted screw	Screw breaker against slotted head screws	Vertical	4.76
160	Screw connection	Slotted screw	Screw breaker against slotted head screws	West	4.72
161	Screw connection	Slotted screw	Screwdriver against slotted head screws	East	4.82
162	Screw connection	Slotted screw	Screwdriver against slotted head screws	North	4.80
163	Screw connection	Slotted screw	Screwdriver against slotted head screws	South	4.76
164	Screw connection	Slotted screw	Screwdriver against slotted head screws	Vertical	4.83
165	Screw connection	Slotted screw	Screwdriver against slotted head screws	West	4.78
166	Screw connection	Slotted screw	Shell bit	East	4.29
167	Screw connection	Slotted screw	Shell bit	North	4.35
168	Screw connection	Slotted screw	Shell bit	South	4.52
169	Screw connection	Slotted screw	Shell bit	Vertical	4.21
170	Screw connection	Slotted screw	Shell bit	West	4.39
171	Screw connection	Wing screw	Tooless	East	4.82
172	Screw connection	Wing screw	Tooless	North	4.80
173	Screw connection	Wing screw	Tooless	South	4.76
174	Screw connection	Wing screw	Tooless	Vertical	4.83
175	Screw connection	Wing screw	Tooless	West	4.78
176	Shape joint	Bent shape lock	Chisel	East	4.47
177	Shape joint	Bent shape lock	Chisel	North	4.52
178	Shape joint	Bent shape lock	Chisel	South	4.70
179	Shape joint	Bent shape lock	Chisel	Vertical	4.39
180	Shape joint	Bent shape lock	Chisel	West	4.60
181	Shape joint	Bent shape lock	Pliers	East	2.37
182	Shape joint	Bent shape lock	Pliers	North	2.43
183	Shape joint	Bent shape lock	Pliers	South	2.56
184	Shape joint	Bent shape lock	Pliers	Vertical	2.33
185	Shape joint	Bent shape lock	Pliers	West	2.49
186	Shape joint	Edged connection	Chisel with hammer	East	11.09
187	Shape joint	Edged connection	Chisel with hammer	North	11.15
188	Shape joint	Edged connection	Chisel with hammer	South	11.32

189	Shape joint	Edged connection	Chisel with hammer	Vertical	11.01
190	Shape joint	Edged connection	Chisel with hammer	West	11.22
191	Shape joint	Folded seam connection	Chisel with hammer	East	11.09
192	Shape joint	Folded seam connection	Chisel with hammer	North	11.15
193	Shape joint	Folded seam connection	Chisel with hammer	South	11.32
194	Shape joint	Folded seam connection	Chisel with hammer	Vertical	11.01
195	Shape joint	Folded seam connection	Chisel with hammer	West	11.22
196	Shape joint	Pivot riveted connection	Bolt cutter	East	3.55
197	Shape joint	Pivot riveted connection	Bolt cutter	North	3.61
198	Shape joint	Pivot riveted connection	Bolt cutter	South	3.79
199	Shape joint	Pivot riveted connection	Bolt cutter	Vertical	3.48
200	Shape joint	Pivot riveted connection	Bolt cutter	West	3.71
201	Shape joint	Riveted connection	Shell bit	East	4.29
202	Shape joint	Riveted connection	Shell bit	North	4.35
203	Shape joint	Riveted connection	Shell bit	South	4.52
204	Shape joint	Riveted connection	Shell bit	Vertical	4.21
205	Shape joint	Riveted connection	Shell bit	West	4.45
206	Shape joint	Twisted shape lock	Pliers	East	2.12
207	Shape joint	Twisted shape lock	Pliers	North	2.17
208	Shape joint	Twisted shape lock	Pliers	South	2.31
209	Shape joint	Twisted shape lock	Pliers	Vertical	2.08
210	Shape joint	Twisted shape lock	Pliers	West	2.23
211	Sliding joint	#	Pliers	East	2.60
212	Sliding joint	#	Pliers	North	2.60
213	Sliding joint	#	Pliers	South	2.60
214	Sliding joint	#	Pliers	Vertical	2.60
215	Sliding joint	#	Pliers	West	2.60
216	Sliding joint	#	Tooless	East	0.99
217	Sliding joint	#	Tooless	North	0.99
218	Sliding joint	#	Tooless	South	0.99
219	Sliding joint	#	Tooless	Vertical	0.99
220	Sliding joint	#	Tooless	West	0.99
221	Snap fastener	Type A	Chisel	East	1.86
222	Snap fastener	Type A	Chisel	North	1.92

223	Snap fastener	Type A	Chisel	South	2.06
224	Snap fastener	Type A	Chisel	Vertical	1.83
225	Snap fastener	Type A	Chisel	West	1.98
226	Snap fastener	Type A	Chisel with hammer	East	2.89
227	Snap fastener	Type A	Chisel with hammer	North	2.95
228	Snap fastener	Type A	Chisel with hammer	South	3.13
229	Snap fastener	Type A	Chisel with hammer	Vertical	2.82
230	Snap fastener	Type A	Chisel with hammer	West	3.03
231	Snap fastener	Type A	Pliers	East	2.33
232	Snap fastener	Type A	Pliers	North	2.39
233	Snap fastener	Type A	Pliers	South	2.52
234	Snap fastener	Type A	Pliers	Vertical	2.29
235	Snap fastener	Type A	Pliers	West	2.45
236	Snap fastener	Type A	Tooless	East	0.52
237	Snap fastener	Type A	Tooless	North	0.58
238	Snap fastener	Type A	Tooless	South	0.72
239	Snap fastener	Type A	Tooless	Vertical	0.49
240	Snap fastener	Type A	Tooless	West	0.64
241	Snap fastener	Type B	Chisel with hammer	East	2.89
242	Snap fastener	Type B	Chisel with hammer	North	2.95
243	Snap fastener	Type B	Chisel with hammer	South	3.13
244	Snap fastener	Type B	Chisel with hammer	Vertical	2.82
245	Snap fastener	Type B	Chisel with hammer	West	3.03
246	Snap fastener	Type C	Chisel	East	1.86
247	Snap fastener	Type C	Chisel	North	1.92
248	Snap fastener	Type C	Chisel	South	2.06
249	Snap fastener	Type C	Chisel	Vertical	1.83
250	Snap fastener	Type C	Chisel	West	6.43
251	Snap fastener	Type C	Chisel with hammer	East	2.89
252	Snap fastener	Type C	Chisel with hammer	North	2.95
253	Snap fastener	Type C	Chisel with hammer	South	3.13
254	Snap fastener	Type C	Chisel with hammer	Vertical	2.82
255	Snap fastener	Type C	Chisel with hammer	West	3.03
256	Snap fastener	Type C	Pliers	East	2.33
257	Snap fastener	Type C	Pliers	North	2.39

258	Snap fastener	Type C	Pliers	South	2.52
259	Snap fastener	Type C	Pliers	Vertical	2.29
260	Snap fastener	Type C	Pliers	West	2.45
261	Snap fastener	Type C	Tooless	East	0.52
262	Snap fastener	Type C	Tooless	North	0.58
263	Snap fastener	Type C	Tooless	South	0.72
264	Snap fastener	Type C	Tooless	Vertical	0.49
265	Snap fastener	Type C	Tooless	West	0.64
266	Snap fastener	Type D	Chisel with hammer	East	2.89
267	Snap fastener	Type D	Chisel with hammer	North	2.95
268	Snap fastener	Type D	Chisel with hammer	South	3.13
269	Snap fastener	Type D	Chisel with hammer	Vertical	2.82
270	Snap fastener	Type D	Chisel with hammer	West	3.03
271	Snap fastener	Type D	Diagonal cutting nipper	East	2.19
272	Snap fastener	Type D	Diagonal cutting nipper	North	2.25
273	Snap fastener	Type D	Diagonal cutting nipper	South	2.39
274	Snap fastener	Type D	Diagonal cutting nipper	Vertical	2.12
275	Snap fastener	Type D	Diagonal cutting nipper	West	2.31
276	Snap fastener	Type D	Pliers	East	2.33
277	Snap fastener	Type D	Pliers	North	2.39
278	Snap fastener	Type D	Pliers	South	2.52
279	Snap fastener	Type D	Pliers	Vertical	2.29
280	Snap fastener	Type D	Pliers	West	2.45
281	Snap fastener	Type E	Diagonal cutting nipper	East	2.19
282	Snap fastener	Type E	Diagonal cutting nipper	North	2.25
283	Snap fastener	Type E	Diagonal cutting nipper	South	2.39
284	Snap fastener	Type E	Diagonal cutting nipper	Vertical	2.12
285	Snap fastener	Type E	Diagonal cutting nipper	West	2.31
286	Snap fastener	Type E	Pliers	East	2.33
287	Snap fastener	Type E	Pliers	North	2.39
288	Snap fastener	Type E	Pliers	South	2.52
289	Snap fastener	Type E	Pliers	Vertical	2.29
290	Snap fastener	Type E	Pliers	West	2.45
291	Snap fastener	Type E	Tooless	East	0.52
292	Snap fastener	Type E	Tooless	North	0.58

293	Snap fastener	Type E	Tooless	South	0.72
294	Snap fastener	Type E	Tooless	Vertical	0.49
295	Snap fastener	Type E	Tooless	West	0.64
296	Soldered joint	#	Diagonal cutting nipper	East	2.82
297	Soldered joint	#	Diagonal cutting nipper	North	2.87
298	Soldered joint	#	Diagonal cutting nipper	South	3.05
299	Soldered joint	#	Diagonal cutting nipper	Vertical	2.74
300	Soldered joint	#	Diagonal cutting nipper	West	2.97
301	Soldered joint	#	Soldering copper	East	4.08
302	Soldered joint	#	Soldering copper	North	4.14
303	Soldered joint	#	Soldering copper	South	4.31
304	Soldered joint	#	Soldering copper	Vertical	4.00
305	Soldered joint	#	Soldering copper	West	4.21
306	Twisted up	#	Pliers	East	6.35
307	Twisted up	#	Pliers	North	6.41
308	Twisted up	#	Pliers	South	6.54
309	Twisted up	#	Pliers	Vertical	6.31
310	Twisted up	#	Pliers	West	6.47
311	Welding	Spot Welded plastic	Chisel with hammer	East	3.30
312	Welding	Spot Welded plastic	Chisel with hammer	North	3.36
313	Welding	Spot Welded plastic	Chisel with hammer	South	3.53
314	Welding	Spot Welded plastic	Chisel with hammer	Vertical	3.22
315	Welding	Spot Welded plastic	Chisel with hammer	West	3.44
316	Welding	Spot Welded plastic	Shell bit	East	4.29
317	Welding	Spot Welded plastic	Shell bit	North	4.35
318	Welding	Spot Welded plastic	Shell bit	South	4.52
319	Welding	Spot Welded plastic	Shell bit	Vertical	4.21
320	Welding	Welded plastic	Shell bit	West	4.45
321	Welding	Welded metal	Bolt cutter	East	3.55
322	Welding	Welded metal	Bolt cutter	North	3.61
323	Welding	Welded metal	Bolt cutter	South	3.79
324	Welding	Welded metal	Bolt cutter	Vertical	3.48
325	Welding	Welded metal	Bolt cutter	West	3.71
326	Welding	Welded plastic	Saw	East	3.75
327	Welding	Welded plastic	Saw	North	3.81

328	Welding	Welded plastic	Saw	South	3.98
329	Welding	Welded plastic	Saw	Vertical	3.67
330	Welding	Welded plastic	Saw	West	3.88
331	Wire connection	Flat cable	Diagonal cutting nipper	East	9.92
332	Wire connection	Flat cable	Diagonal cutting nipper	North	10.14
333	Wire connection	Flat cable	Diagonal cutting nipper	South	10.80
334	Wire connection	Flat cable	Diagonal cutting nipper	Vertical	9.65
335	Wire connection	Flat cable	Diagonal cutting nipper	West	10.47
336	Wire connection	Single/integrated cable	Diagonal cutting nipper	East	2.82
337	Wire connection	Single/integrated cable	Diagonal cutting nipper	North	2.87
338	Wire connection	Single/integrated cable	Diagonal cutting nipper	South	3.07
339	Wire connection	Single/integrated cable	Diagonal cutting nipper	Vertical	2.74
340	Wire connection	Single/integrated cable	Diagonal cutting nipper	West	2.97

A.5 Case Problem: Data Sheet

(See **Table A-29**).

Table A-29: The wheel mouse: parts recycling profit.

1	$		ton	ton	lbs	lbs	lbs	ton	ton	ton	
0.823503	€		-20	-200	0.12	0.25	0.01	120	1,260	7.5	$
			Normal Landfill	**Hazardous Landfill**	**ABS Scrap**	**No.3 Insulated Copper Wire**	**Mixed Unsortable Plastic Scrap**	**No.4 Shredded Steel shall consist of coarse shredded steel scrap**	**Populated Circuit Boards**	**Mixed WEEE Scrap & Mixed Components (sheared or dismantled)**	
	1	ton						98.820360000	1,037.613780000	6.176272500	€
	1,000	kg						98.820360000	1,037.613780000	6.176272500	€
	1,000,000	g						98.820360000	1,037.613780000	6.176272500	€
	1	g						0.000098820	0.001037614	0.000006176	€
	1	pounds (lbs)			0.098820360	0.205875750	0.008235030				€
	0.453592	kg			0.098820360	0.205875750	0.008235030				€
	453.592	g			0.098820360	0.205875750	0.008235030				€
	1	g			0.000217862	0.000453879	0.000018155				€
Material											
Plastic (ABS)	19.00	g	-0.000312931		0.004139374						€
Plastic (ABS)	3.00	g	-0.000049410		0.000653585						€
Plastic (ABS)	3.00	g	-0.000049410		0.000653585						€
Plastic (Unidentified)	4.50	g	-0.000074115				0.000081698				€
Plastic (Unidentified) + IC	1.30	g		-0.000214111						0.000008029	€
Insulated Wires	31.00	g	-0.000510572			0.014070240					€
Insulated Wires	1.10	g	-0.000018117			0.000499267					€
PCB	14.00	g		-0.002305808					0.014526593		€
Metal + Epoxy Coated	32.00	g	-0.000527042					0.003162252			€
Plastic (ABS)	19.50	g	-0.000321166		0.004248305						€
Plastic (ABS)	1.50	g	-0.000024705		0.000326793						€
Total	**129.90**	**g**	**-0.001887469**	**-0.002519919**	**0.010021642**	**0.014569506**	**0.000081698**	**0.003162252**	**0.014526593**	**0.000008029**	€

With minimum EOL operation costs (source: Lee, 1995; Scrapindex.com; Xe.com, 2005).

Appendix B

General Concerns Related to ReOAT

B.1 WEEE Directive

The WEEE Directive 2002/96/EC defines strict processing and recycling quotas. Member States shall ensure that their processing and recycling quotas will be met by 31st December 2006 (see **Table B-1**).

Table B-1: WEEE Directive 2002/96/EC processing quotas

Equipment category	Processing quota (%)	Recycling quota (%)
Large domestic appliances	80	75
Small domestic appliances	70	50
IT and telecommunications equipment	75	65
Entertainment equipment	75	65

Every year, approximately 2 million tones of electronic waste are collected in Germany. This quantity corresponds to a fully loaded train with the length of 2,000 km. One fifth of this waste is made up of plastics (Mäurer, 2004). These plastics cannot be re-used, because they appear as "mixed waste", contaminated with undesired flame retardants. In Germany, out of 59,000 tones registered plastics from the collected electrical and electronic wastes of the officially assigned collecting companies, only 5,000 tones were processed and 54,000 tones waste-handled (Landry, 2004). With such a performance, the recycling quotas of 65 to 75% as requested by the European Directive for Waste Electrical and Electronic Equipments (WEEE) will not be met, and the target is still too far to be met. Due to the high content of impurities and contaminants, they are classified as requiring "special control" and have to be waste-handled at a high cost, though they represent a potentially high value resource of approximately 400 million Euros (Mäurer, 2004), if the contaminants could be removed.

B.2 RoHS Directive

Regarding electronic manufacturers, besides heavy metals (Pb, Cd, and PCB), that are toxic and phased out by RoHS Directive (Directive 2002/95/EC), flame-retardants play an important role in electronic products. From most of the modern wiring board (PWB) technology, where flame-retardant is required with limited used in thermoplastics, tetrabromobisphenol (TBBA) is the largest (by commercial value) flame-retardants sold in the marketplace. 78% of the flame-retardants consist of brominated compounds (Landry, 2004). This industrial sector has been using TBBA for over thirty years and the product performs well. Recently, however, TBBA together with Brominated flame-retardants in general is perceived as having some negative toxic risk assessment when released to the environment (Blundell, 2004). As long as the removal of inner contaminants by appropriate technologies is not available, till date WEEE plastic scrap containing brominated additives is required to be excluded from material recovery because of the risk of exceeding toxic standard thresholds. Example of brominated plastic structure e.g., polybrominated dibenzo-p-dioxins (PBDDs) and polybrominated furans (PBDFs) in recycled plastics are displayed as follows (see **Figure B-1**).

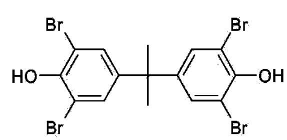
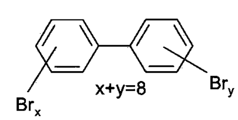
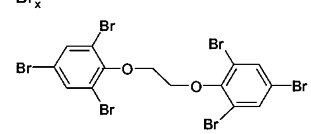
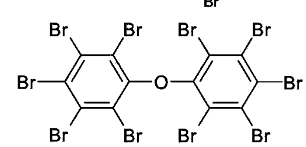
Low potential PBDD/F formation	High potential for PBDD/F formation
 TBBPA	 PBB  TBPE  PBDE

Figure B-1: Structure of different flame retardants with varying potential for PBDD/F formation (source: modified from Mäurer, 2004.)

Nevertheless, flame-retardants are unequivocally of great benefit to humankind since their applications in polymers and textiles have led to a significant reduction of fire cases and death causalities related to fire. However, brominated flame-retardants have to be phased out and alternatives found. Some developments of new halogen-free (Phosphorus-based flame-retardants, Inorganic mineral-based flame retardant), and new flame-retardant resins are ongoing, which have low environmental impacts. At the initial state of new resins production, the prices are expensive. In general, to trim down prices, there should be an increase in production.

B.3 Sustainable Development in Plastics

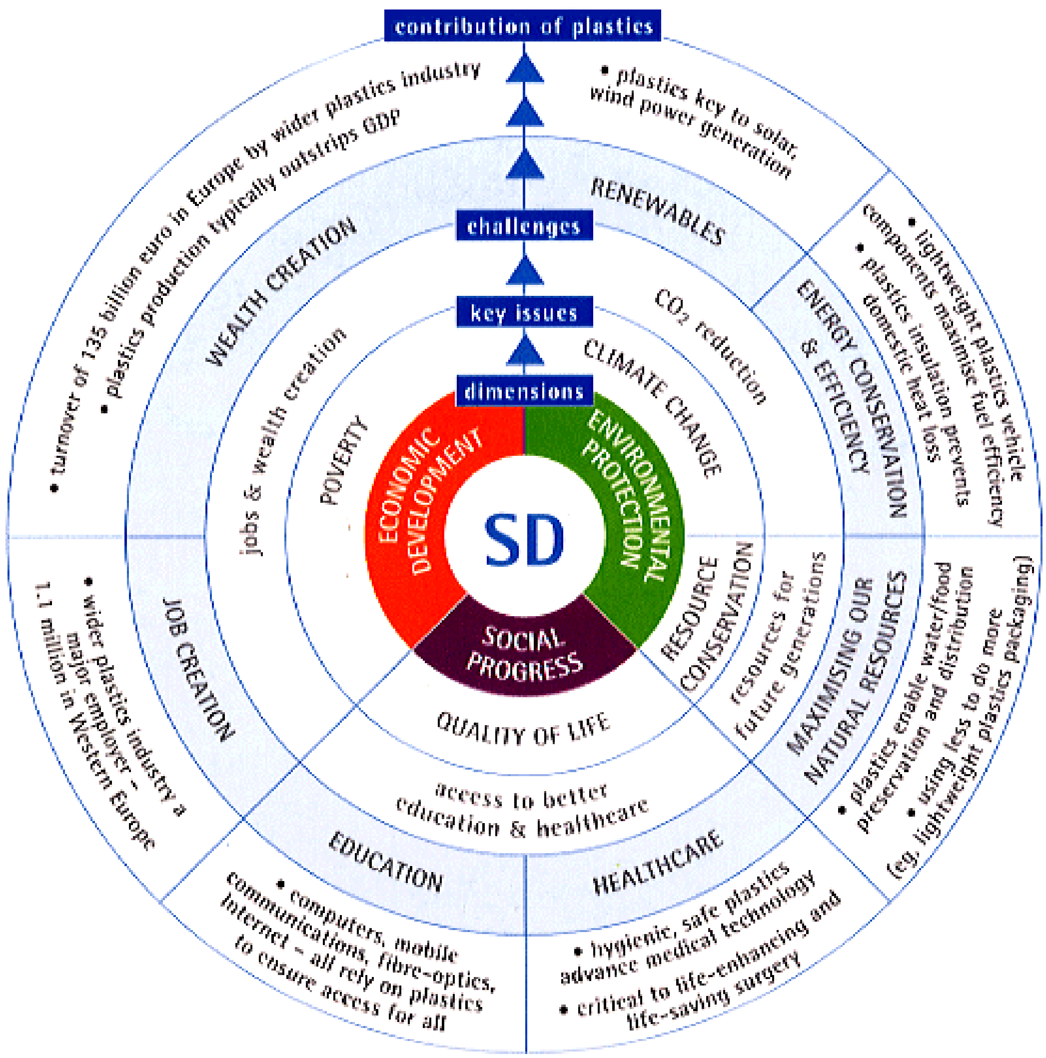
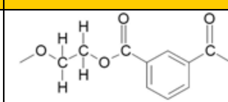
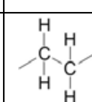
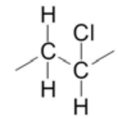
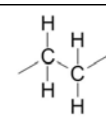


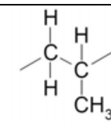
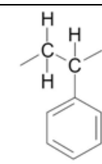
Figure B-2: Sustainable Development with Plastics (source: APC, 2004).

B.4 Resin Identification Codes - Plastic Recycling Codes

Table B-2: Resin Identification Codes - Plastic Recycling Codes (source: modified from APC, 2004b).

Codes	Descriptions	Properties	Packaging Applications	Recycled Products	Structure
1 PETE	Polyethylene Terephthalate (PET, PETE). PET is clear, tough, and has good gas and moisture barrier properties. Commonly used in soft drink bottles and many injection molded consumer product containers. Other applications include strapping and both food and non-food containers. Cleaned, recycled PET flakes and pellets are in great demand for spinning fiber for carpet yarns, producing fiberfill and geo-textiles. Nickname: Polyester.	Clarity, strength, toughness, barrier to gas and moisture, resistance to heat	Plastic soft drink, water, sports drink, beer, mouthwash, catsup and salad dressing bottles. Peanut butter, pickle, jelly and jam jars. Ovenable film and ovenable prepared food trays.	Fiber, tote bags, clothing, film and sheet, food and beverage containers, carpet, strapping, fleece wear, luggage and bottles.	
2 HDPE	High Density Polyethylene (HDPE). HDPE is used to make bottles for milk, juice, water and laundry products. Unpigmented bottles are translucent, have good barrier properties and stiffness, and are well suited to packaging products with a short shelf life such as milk. Because HDPE has good chemical resistance, it is used for packaging many household and industrial chemicals such as detergents and	Stiffness, strength, toughness, resistance to chemicals and moisture, permeability to gas, ease of processing, and ease of forming.	Milk, water, juice, cosmetic, shampoo, dish and laundry detergent bottles; yogurt and margarine tubs; cereal box liners; grocery, trash and retail bags.	Liquid laundry detergent, shampoo, conditioner and motor oil bottles; pipe, buckets, crates, flower pots, garden edging, film and sheet, recycling bins, benches, dog houses, plastic lumber, floor tiles, picnic tables, fencing.	

	bleach. Pigmented HDPE bottles have better stress crack resistance than unpigmented HDPE bottles.				
3 V	Vinyl (Polyvinyl Chloride or PVC): In addition to its stable physical properties, PVC has excellent chemical resistance, good weatherability, flow characteristics and stable electrical properties. The diverse slate of vinyl products can be broadly divided into rigid and flexible materials. Bottles and packaging sheet are major rigid markets, but it is also widely used in the construction market for such applications as pipes and fittings, siding, carpet backing and windows. Flexible vinyl is used in wire and cable insulation, film and sheet, floor coverings synthetic leather products, coatings, blood bags, medical tubing and many other applications.	Versatility, clarity, ease of blending, strength, toughness, resistance to grease, oil and chemicals.	Clear food and non-food packaging, medical tubing, wire and cable insulation, film and sheet, construction products such as pipes, fittings, siding, floor tiles, carpet backing and window frames..	Packaging, loose-leaf binders, decking, paneling, gutters, mud flaps, film and sheet, floor tiles and mats, resilient flooring, cassette trays, electrical boxes, cables, traffic cones, garden hose, mobile home skirting.	
4 LDPE	Low Density Polyethylene (LDPE).Used predominately in film applications due to its toughness, flexibility and relative transparency, making it popular for use in applications where heat sealing is necessary. LDPE is also used to manufacture some flexible lids and	Ease of processing, strength, toughness, flexibility, ease of sealing, barrier to moisture.	Dry cleaning, bread and frozen food bags, squeezable bottles, e.g. honey, mustard.	Shipping envelopes, garbage can liners, floor tile, furniture, film and sheet, compost bins, paneling, trash cans, landscape timber, lumber	

	bottles and it is used in wire and cable applications				
5 PP	Polypropylene (PP). Polypropylene has good chemical resistance, is strong, and has a high melting point making it good for hot-fill liquids. PP is found in flexible and rigid packaging to fibers and large molded parts for automotive and consumer products.	Strength, toughness, resistance to heat, chemicals, grease and oil, versatile, barrier to moisture.	Catsup bottles, yogurt containers and margarine tubs, medicine bottles	Automobile battery cases, signal lights, battery cables, brooms, brushes, ice scrapers, oil funnels, bicycle racks, rakes, bins, pallets, sheeting, trays.	
6 PS	Polystyrene (PS). Polystyrene is a versatile plastic that can be rigid or foamed. General purpose polystyrene is clear, hard and brittle. It has a relatively low melting point. Typical applications include protective packaging, containers, lids, cups, bottles and trays.	Versatility, insulation, clarity, easily formed	Compact disc jackets, food service applications, grocery store meat trays, egg cartons, aspirin bottles, cups, plates, cutlery.	Thermometers, light switch plates, thermal insulation, egg cartons, vents, desk trays, rulers, license plate frames, foam packing, foam plates, cups, utensils	
7 OTHER	Other. Use of this code indicates that the package in question is made with a resin other than the six listed above, or is made of more than one resin listed above, and used in a multi-layer combination.	Dependent on resin or combination of resins	Three and five gallon reusable water bottles, some citrus juice and catsup bottles.	Bottles, plastic lumber applications.	

B.5 Will the hydrocarbon era finish soon?

H. Rempel (2000) carried out a research on different forecasts for oil production (see **Figure B-3**). The research can be used to point out on: will the hydrocarbon era finish soon?

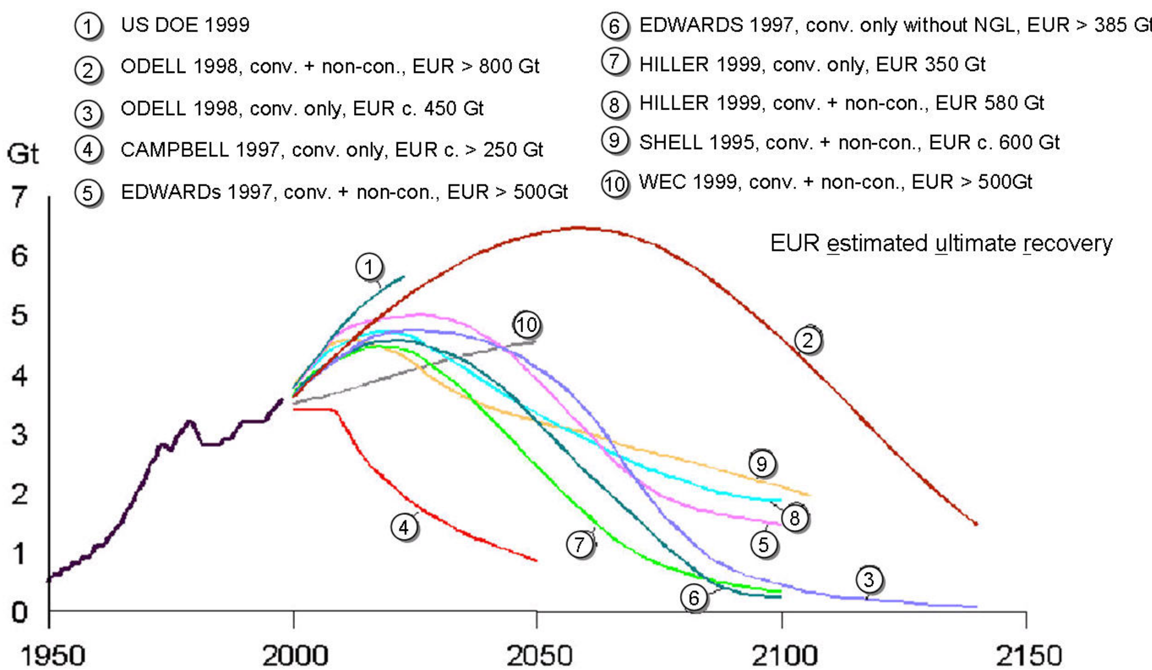


Figure B-3: Different scenarios for crude oil demand and production based conventional and non-conventional oil (source: modified from Rempel, 2000).

The figure forecasts for production of conventional oil as well as the combination of conventional and non-conventional oil is shown. Most curves show that the maximum oil production will be reached during the period from 2010 to 2020. Only the Odell (curve No.2) differs from the common picture and forecast a maximum at 2070 based on production of conventional and non-conventional oil with estimated ultimate recovery (EUR) of 800 billion tons (Rempel, 2000).

In the 21st century the world must solve two great problems e.g., (1) Overpopulation in the developing world; (2) Overconsumption in the developed world. The developing world has, on the other hand 80% of the world's population and consumes 20% of its resources. The developed world has 20% of the world's population and consumes 80% of its resources (Fisker, 2005). Yearly we are consuming so much oil and gas as the nature produced in several million years. **Figure B-4** shows schematically the oil production clearly the period between the birth of Christ and the year 2500. In this scale, the hydrocarbon era is a short episode (Rempel, 2000).

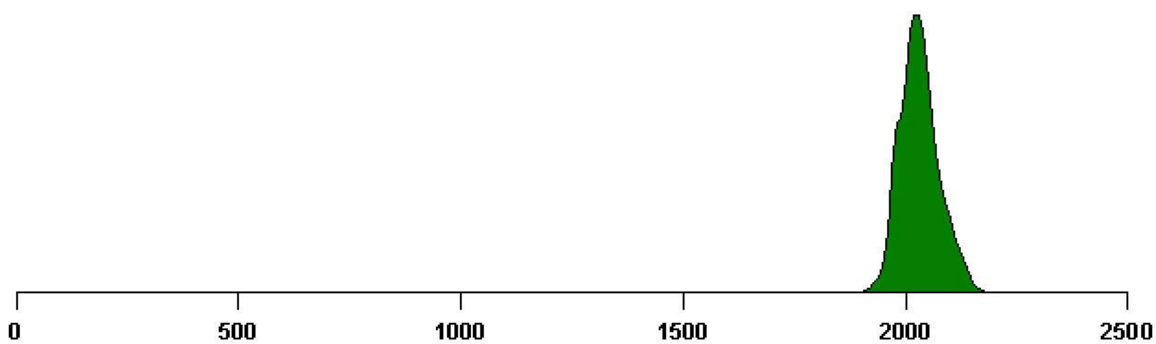


Figure B-4: Oil production in the timeframe between birth of Christ and the year 2500 (source: Rempel, 2000).

"Jon Thompson, President of ExxonMobil Exploration Company states that: ...we estimate that world oil and gas production from existing fields is declining at an average rate of about 4 to 6 percent a year. To meet projected demand in 2015, the oil industry will have to add about 100 million oil-equivalent barrels a day of new production. That is equal to about 80 percent of today's production level. In other words, by 2015, we will need to find, develop and produce a volume of new oil and gas that is equal to eight out of every 10 barrels being produced today. In addition, the cost associated with providing this additional oil and gas is expected to be considerably more than what industry is now spending. Equally daunting is the fact that many of the most promising prospects are far from major markets - some in regions that lack even basic infrastructure. Others are in extreme climates, such as the Arctic, that present extraordinary technical challenges" (Fisker, 2005).

Appendix C

ReOAT Support

C.1 Online Support

Launch online support on 19 May 2005 (see **Figure C-1**).

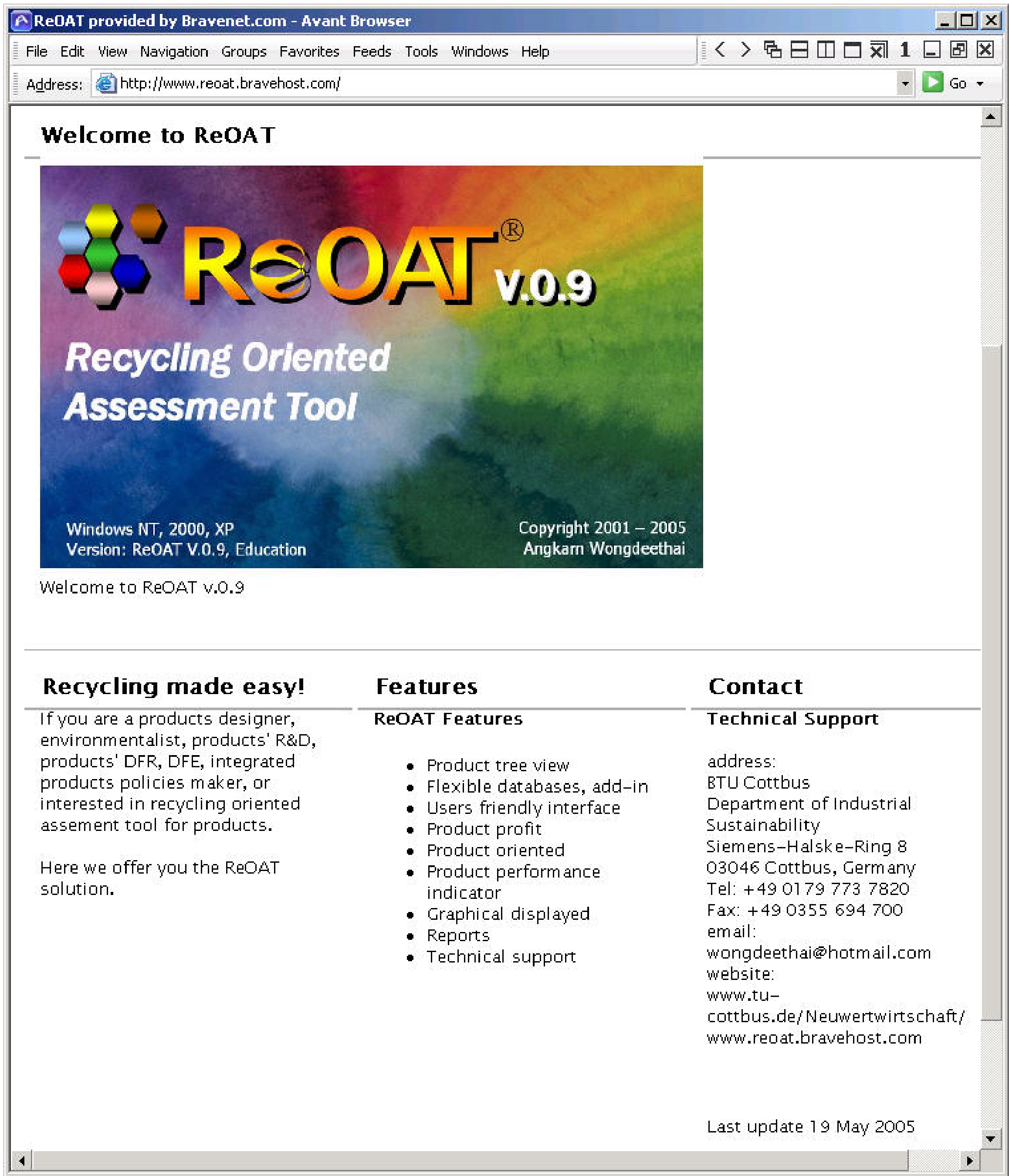


Figure C-1: Online help and support at www.reoat.bravehost.com

Curriculum Vitae

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Born in 1977, 1999 Bachelor in Civil Engineering, Study of Civil Engineering at the Sirinhorn International Institute of Technology Thammasat University, Thailand. 2002 Master of Science, Study of Environmental and Resource Management at the Brandenburg University of Technology Cottbus, Germany. Since 2002 Lecturer and Research Associate at the Department of Industrial Sustainability, Brandenburg University of Technology Cottbus, Germany.